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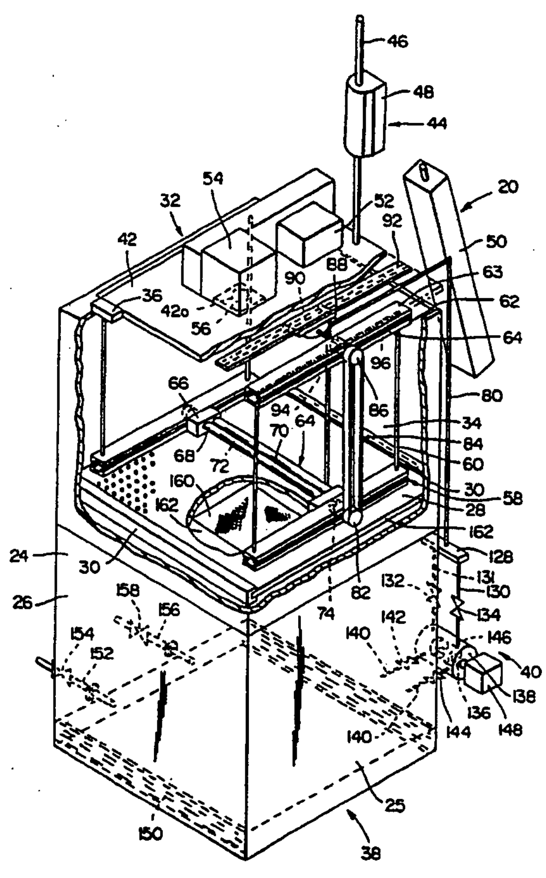
(54) Title: METHOD OF AND APPARATUS FOR FORMING A SOLID THREE-DIMENSIONAL ARTICLE FROM A LIQUID MEDIUM

(57) Abstract

A method and apparatus (20) for forming a solid three-dimensional article by exposure of successive layers of a liquid material to a vertically movable energy source (32). The apparatus includes a fixed support plate (28) disposed in a container (24), the liquid being dispensed to successively higher levels in the container above the plate. In one embodiment, the liquid is fed from a reservoir (25) below the plate to an upper portion of the container above the plate by an expandable member (150) disposed in the reservoir. A vertically movable liquid dispenser (34) may be provided above the plate either alone or in combination with the expandable member. The energy source includes a laser (50), a focusing optics system (52) and a scanner head (54) for directing a laser beam to solidify selected portions of successive layers of the liquid medium.



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METHOD OF AND APPARATUS FOR FORMING A SOLID THREE-DIMENSIONAL ARTICLE FROM A LIQUID MEDIUM

This application is a continuation-in-part of U.S. patent application Serial No. 07/479,702, filed February 15, 1990.

BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

This invention relates to a method of and apparatus for forming a solid three-dimensional article from a liquid medium, and more particularly to a method of and apparatus for forming a solid three-dimensional article from a liquid medium capable of solidification when subjected to prescribed energy, wherein the article can be formed in an accurate, rapid and expeditious manner as compared to prior known systems.

DESCRIPTION OF THE PRIOR ART

In general, apparatus for forming a solid three-dimensional article from a liquid medium capable of solidification when subjected to prescribed energy, are known in the prior art. For example, U.S. Patent No. 2,775,578 to O.J. Munz discloses a system for generating three-dimensional objects from a liquid medium by irradiating liquid layers with the aid of a computer programmed irradiation source and a translational mechanism. Other arrangements of this general type are disclosed in an article by H. Kodama, entitled "Automatic Method for Fabricating a Three-Dimensional Plastic Model with Photo-Hardening Polymer", Review Scientific Instruments, Vol. 52, No. 11, November 1981, pages 1770-1773, and an article by A. J. Herbert, entitled "Solid Object Generation", Journal of Applied Photographic Engineering 8 (4) August 1982, pages 185-188. A similar arrangement is disclosed in reexamined U.S. Patent No. 4,575,330 to C. W. Hull, in which Reexamination

Certificate B1 4,575,330, was issued on December 19, 1989.Other prior art of interest includes the U.S. Patents Nos. 2,525,532 to Dreywood, 2,381,234 to Symmes, 3,723,120 to Hummel, 3,609,707 to Lewis et al, 4,081,276 to Crivello and 4,252,514 to Gates, and the British Patent No. 566,795 to Gates.

However, a need still exists for a method of and apparatus for forming a solid three-dimensional article from a liquid medium in an accurate, rapid and expeditious manner, with a minimum of waste in time and material, and a primary purpose of this invention is to provide such a method and apparatus.

SUMMARY OF THE INVENTION

In general, the subject invention relates to a method of and apparatus for forming a solid three-dimensional article from a liquid medium capable of solidification when subjected to prescribed energy, wherein by way of illustration, a fixed support may be provided in a container for holding the liquid medium. A layer of the liquid medium in the container then is produced above the fixed support, and a preselected cross-section of the layer is solidified by exposing at least a portion of the layer to prescribed energy in accordance with a design for the three-dimensional article. The liquid medium layer-producing and solidifying steps then are repeated, as necessary, to form the solid three-dimensional article. Each layer of the liquid medium is produced either partially, or entirely, by dispensing the liquid medium from above the support.

For example, in one embodiment in accordance with the invention, a first incremental layer of the liquid medium is initially coated on a support. A preselected cross-section of the first incremental layer of the liquid medium then is solidified by exposing at least a portion

of the layer to prescribed energy, to form a first cross-section of the solid three-dimensional article. The level of the liquid medium surrounding the solidified first cross-section then is raised so as to form a meniscus around the periphery of the first cross-section. Next, the solidified first cross-section is coated with a second incremental layer of the liquid medium, so that the meniscus surrounding the solidified cross-section is broken and the second incremental layer of the liquid medium and the liquid medium surrounding the second cross-section flow together. This is followed by solidifying a second preselected cross-section of the liquid medium by exposing the liquid medium to prescribed energy, to form a second cross-section of the solid three-dimensional article. Thereafter, the liquid medium level raising, liquid medium coating and liquid medium solidifying operations, are repeated, as necessary, to complete the three-dimensional article.

In another embodiment in accordance with invention, each layer of the liquid medium is produced above a fixed support in the container for holding the liquid medium, by dispensing the entire layer from above the fixed support in the container, across the entire width of the container. A preselected cross-section of the layer then is solidified by exposing at least a portion of the layer to prescribed energy in accordance with a design for the three-dimensional article. The liquid medium layer-producing and solidifying steps then are repeated, as necessary, to form the solid three-dimensional article.

More specifically, the coating of the first incremental layer on the support and the subsequent liquid medium coating steps in the alternative embodiment, may be performed by spraying or another type of dispensing operation, while the solidifying steps are

performed by lasering, using a laser beam which may be controlled by an RF laser beam modulator. The liquid medium is held in the container, and the support for the solid three-dimensional article as it is formed, is of apertured construction and removably mounted in a fixed position in the container. One type of coating mechanism may be in the form of an elongated apertured tube, which has aperture-closing pins selectively operated by solenoids, or which has rows of small dispensing apertures of a size such that the liquid medium flows therefrom only under pressure. The apertured tube also may be positioned closely adjacent the previously coated layer so that the liquid medium is dispensed from the tube in a uniform, controlled manner by capillary action and surface tension. In the alternative, the coating mechanism may be in the form of an outer elongated cylinder and an inner elongated cylinder mounted in relatively rotatable coaxial relationship, with each cylinder including an elongated slot, and with a mechanism for causing relative rotation between the cylinders to cause relative movement of the elongated slots between a non-aligned closed relationship and an aligned coating relationship.

Further, the liquid medium may be fed to the coating mechanism by a mechanism for withdrawing liquid medium from a lower portion of the container or a separate lower container, and feeding the liquid medium to the coating mechanism. The withdrawing-and-feeding mechanism may include a double acting piston in a cylinder and include valves for controlling flow of the liquid medium to and from the piston and cylinder, or may be a digital metering pump. The coating mechanism may be mounted for horizontal reciprocating movement above the support by a gear rack or ball screw mechanism and associated drive,

or may be mounted for oscillating swinging movement above the support. Raising of the liquid level in the container in the first embodiment may be accomplished by an expandable member, such as a bellows in the bottom portion of the associated container and operable in response to fluid pressure, and the solidifying mechanism and the coating mechanism in both of the embodiments may be mounted for vertical movement relative to the article support.

BRIEF DESCRIPTION OF DRAWINGS OF PREFERRED EMBODIMENTS OF THE INVENTION

Figure 1 is an isometric, schematic view of a first embodiment of an apparatus for forming a solid three-dimensional article from a liquid medium in accordance with the invention;

Figure 2 is a plan view of the apparatus shown in Figure 1, with certain parts omitted or partially broken away;

Figure 3 is an enlarged isometric view of a coating mechanism of the apparatus shown in Figure 1, for applying successive coatings of the liquid medium in the forming of the solid three-dimensional article;

Figure 4 is an isometric view, similar to Figure 1, showing an alternate form of coating mechanism to that shown in Figures 1-3;

Figure 5A is an enlarged, schematic, partial view of an apertured spray tube-type coating mechanism as shown in Figure 3;

Figure 5B is a cross-sectional view taken along the lines 5B-5B in Figure 5A;

Figure 5C is an enlarged, schematic, partial view of an alternate spray tube construction;

Figure 5D is a cross-sectional view taken along the line 5D-5D in Figure 5C;

Figure 6 is an enlarged, schematic, partial view of a slot-type coating mechanism;

Figures 7A and 7B are schematic cross-sectional views taken along the line 7-7 in Figure 6 showing different operating conditions;

Figures 8 through 13 are elevational schematic views illustrating a sequence of steps in the forming of the solid three-dimensional article, in accordance with the first embodiment of the invention;

Figure 14 is a block diagram further illustrating the sequence of steps shown in Figures 8 through 13;

Figure 15 is a schematic illustration of an optics system which may be used in practicing the invention;

Figure 16 is a block diagram of a system for carrying out the invention;

Figure 17 is a flow chart illustrating a sequence of programming steps utilized in carrying out the first embodiment of the invention;

Figures 18A and 18B are isometric views of solid three-dimensional articles illustrating various types of shapes which may be formed utilizing the subject invention;

Figure 19 is a schematic front elevational view of a second embodiment of the invention;

Figures 20 through 24 are elevational schematic views similar to Figure 19, illustrating a sequence of steps in the forming of a solid three-dimensional article, in accordance with the second embodiment of the invention, but with a vertical central portion of the apparatus turned 90° and shown as viewed along the line 20-20 in Figure 19;

Figure 25 is an isometric view of a modified type of liquid medium coating mechanism which may be used in the second embodiment of the invention shown in Figures 19-24;

Figure 26 is a view of the bottom of a liquid medium dispensing tube of the coating mechanism shown in Figure 25, as seen along the line 26-26;

Figure 27 is an enlarged schematic view illustrating a mode of operation of the liquid medium dispensing tube of the coating mechanism shown in Figures 25 and 26;

Figure 28 is a schematic view illustrating the path of a laser beam in solidifying a cross-sectional layer of the liquid medium;

Figures 29A and 29B are elevational views of articles each having a downwardly facing surface, illustrating a laser beam offset feature of the invention;

Figures 30A, B, C and D are schematic views illustrating an article curved surface interpolation feature of the invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

Referring to the embodiment of the invention shown in Figures 1 and 2, an apparatus 20 in accordance with the invention, for forming solid three-dimensional articles or parts, such as a turbine blade 22a, as illustrated in Figure 18A, or a jet fuel swirler 22b, as illustrated in Figure 18B, is disclosed. The apparatus 20 includes a container or tank 24, having a lower sump portion 25 (Figure 1), for holding a liquid medium 26. The container 24 includes a horizontally disposed apertured support plate member 28, for supporting the article 22 being formed during a forming operation. The support plate member 28 is removably mounted (through a door, not shown) in the container 24 in a fixed position against vertical movement, at an intermediate level, such as by having peripheral edge portions received in slotted guide members 30 (Figure 1) fixed to the container interior walls. The apparatus 20 further includes a vertically

movable energy scanning mechanism or system 32 for solidifying successive preselected cross-sections of the liquid medium 26, to form one of the articles 22. A liquid medium coating mechanism 34 and a liquid medium level sensor 36 (Figure 1) of a laser beam-emitting type, which is responsive to reflected laser light from the surface of the liquid medium 26, are mounted on the vertically movable scanning mechanism 32. As is shown in Figure 1, a liquid medium level raising mechanism 38 is provided in the bottom of the container 24, and a liquid medium withdrawal-and-feeding mechanism 40 also is provided adjacent the lower end of the container exteriorly thereof.

The vertically movable scanning mechanism 32 comprises a horizontal support plate 42 which is connected to a vertical traversing mechanism 44, such as a screw-threaded member 46 driven vertically by a reversible motor 48, for raising and lowering the scanning mechanism. A source of energy, such as a laser 50, a laser beam focusing optics system 52 and a scanner head 54, for directing the laser beam energy to solidify successive layers of the liquid medium 26, are all also mounted on the support plate 42 in a suitable manner. The horizontally disposed support plate 42 has an opening 42o formed therein beneath the scanner head 54, and is provided on its underside with a shutter 56 which is movable to an open position for a scanning operation, and movable to a closed position during the liquid medium coating operation, to prevent extraneous liquid medium from contaminating the optics system 52. For example, the shutter 56 may be secured to one end of a pivoted lever (not shown) pivotably connected at its opposite end to a solenoid (not shown) mounted beneath the support plate 42.

Referring to Figures 1 and 2, the liquid medium coating mechanism 34 may comprise a sub-frame 58 suspended beneath the horizontal plate 42. The sub-frame 58 includes a plurality of depending vertical legs 60 at each corner of the support plate 42, and horizontally disposed gear racks 62 and respective opposed guide members 63 connected between lower ends of respective ones of the vertical legs. The coating mechanism 34 further includes a coating carriage 64 of rectangular rigid construction, comprising opposite end plates 66, a drive shaft-enclosing tube 68 defining one longitudinal side of the carriage, and a liquid medium dispensing mechanism in the form of a spray tube 70 defining the opposite longitudinal side. The carriage 64 extends between the gear racks 62 and guide members 63 and further includes a drive shaft 72 journaled in the end plates 66 and having drive pinion gears 74 fixed thereto adjacent its opposite ends. The pinion gears 74 are disposed between respective ones of the opposed gear racks 62 and guide members 63, which thus guide the coating carriage 64 for horizontal movement therebetween. An idler pinion gear 76 (best shown in Figures 2 and 3) is rotatably mounted on a stub shaft 78 projecting from each end plate 66 and also is disposed between the adjacent gear racks 62 and guide members 63, to maintain the coating carriage 64 against rotation about the drive shaft 72, during the horizontal movement of the spray tube 70. The liquid medium 26 is fed into the spray tube 70 via a flexible line 80.

As is best shown in Figure 3, an extended portion of the drive shaft 72 has a drive pulley 82 fixed thereto and connected by a timing belt 84 to a pulley 86 secured to a drive shaft 88 of a small reversible motor 90 mounted for sliding movement on a dove-tail guide 92

secured to the underside of the horizontally disposed support plate 42. The drive shaft 88 of the motor 90 also has a pinion gear 94 secured thereon and engageable with a horizontally disposed gear rack 96 extending between and fixedly connected to adjacent ones of the vertical legs 60 below the horizontal plate member 42. Accordingly, during a liquid medium coating operation, rotation of the motor 90 causes it to drive itself along its guide 92 by engagement of its drive pinion gear 94 with the gear rack 96, while at the same time, causing the coating carriage 64 to be driven along the lower gear ~~racks 62 by means of the timing belt 84,~~ and the pulley 82 and pinion gears 74 on the coating carriage 64.

Figure 4 discloses an alternative embodiment of the coating mechanism of the invention in which a cylindrical spray tube 70' of a coating mechanism 34' is mounted beneath a horizontal support plate 42' by a pendulum-type oscillating mounting 98. In this embodiment, opposite ends of the spray tube 70' are secured to a pair of horizontally spaced vertically depending legs 100 secured at their upper ends to a horizontal rotatable shaft 102 mounted in suitable bearings 104 secured to the underside of the horizontal support plate 42'. The rotatable shaft 102 forms a drive shaft of a small reversible motor 106 fixedly mounted on the underside of the horizontal support plate 42'. Thus, by operating the motor 106 through a preselected angle, such as 40°, the spray tube 70' can be moved along an arc for spraying liquid medium 26 toward an apertured article support plate (not shown in Figure 4) in a liquid medium-coating operation.

As is illustrated in Figures 5A and 5B, each of the spray tubes 70 or 70' may include a row of spraying apertures 108 extending along a lower portion thereof, with the liquid medium flexible inlet tube 80 connected

to the spray tube adjacent one end thereof. In the alternative, referring to Figures 6, 7A and 7B, each of the spray tubes 70 or 70' may be in the form of a cylinder assembly 110 comprising an outer cylinder 112 provided with an elongated slot 114, and an inner cylinder 116 also provided with an elongated slot 118. The inner cylinder 116 is rotatable relative to the outer cylinder 112 between a position in which the elongated slots 114 and 118 in the cylinders are aligned, as shown in Figure 7A, for a spraying operation, and a relative position in which the slots are in a non-aligned closed position, as shown in Figure 7B. For this purpose, a small solenoid 120 is fixedly mounted on the outer cylinder 112 and has an arc-shaped plunger 122 pivotally connected to an outer end of a lug 124 secured at its inner end to the inner cylinder 116, with the lug disposed for limited circumferential movement in a circumferentially extending slot 126 in the outer cylinder.

Referring again to Figure 1, the liquid medium 26 for a liquid medium coating operation is provided to the spray tube 70 by the liquid medium withdrawing-and-feeding mechanism 40. For this purpose, as is illustrated by the spray tube inlet line 80, the inlet line is connected to a manifold 128, in turn connected by feed lines 130 and 131 and respective control valves 132 and 134 to a double acting piston-and-cylinder mechanism 136. A cylinder 138 of the double acting piston-and-cylinder mechanism 136 is connected by additional feed lines 140, through control valves 142 and 144, to the liquid medium sump portion 25 adjacent the bottom of the liquid medium container 24. A double acting piston 146 of the piston-and-cylinder mechanism 136 is reciprocated by a solenoid 148, so that, upon

selective operation of the valves 132, 134, 142 and 144, when the piston is moved in one direction (e.g., to the left in Figure 1) with the valves 132 and 144 open and the valves 134 and 142 closed, the liquid medium 26 in the cylinder 138 will be forced from the cylinder through the valve 132, the feed line 131, the manifold 128 and the inlet tube 80 to the spray tube 70. At the same time, with the valve 144 open and the valve 134 closed, additional liquid medium 26 will be withdrawn from the sump portion of the container 24 into the opposite end of the cylinder 138. Then, upon a next liquid medium coating operation, when the solenoid 148 is operated to move the piston 136 in the opposite direction (i.e., to the right in Figure 1), with the valves 134 and 142 open and the valves 132 and 144 closed, the liquid medium 26 which was withdrawn into the cylinder 138 on the previous coating operation, will be fed from the cylinder through the valve 134, the feed line 130, the manifold 128 and the inlet tube 80, to the spray tube 70.

With further reference to Figure 1, the liquid level raising mechanism 38 comprises an expandable member, such as a bellows 150, disposed in the bottom of the liquid medium container 24. One end of the bellows 150 is connected by an inlet line 152 extending through a lower wall portion of the container 24, and a control valve 154, to a fluid pressure source, such as air or water, not shown. Accordingly, when the control valve 154 is opened, the bellows 150 is expanded by the fluid pressure an incremental amount in order to raise the level of the liquid medium 26 in the container 24 a corresponding incremental amount (e.g., 0.0017" to .020") above the upper surface of the apertured article support plate 28 in the container for an article layer forming operation. For this purpose, the liquid medium level sensor 36 on

the vertically movable scanning mechanism 32, operates when the desired liquid medium incremental level above the surface of the support plate 28 has been reached, to cause closing of the bellows control valve 154. This expansion of the bellows 150 is repeated for subsequent article layer forming operations until forming of the article 22 has been completed and the upper surface of the bellows has reached an upper level. A drain line 156 with a valve 158, which also is connected to the bellows 150, then may be opened to drain the expansion fluid therefrom, whereupon the bellows returns to its original un-expanded condition, as shown in solid lines in Figure 1, and the liquid medium 26 in the container 24 is returned to its original lower position. During this liquid level returning operation, any extraneous solidified material in the article-forming upper portion of the container 24 is removed by a filter 160 disposed in a horizontal plate 162 secured to the interior walls of the container.

Figures 8-13 are schematic illustrations depicting a series of steps in carrying out the method of the invention, and Figure 14 is a block diagram summarizing the steps illustrated in Figures 8-13. With reference to Figure 8, initially, a first layer 164 of the liquid medium 26 is applied to the apertured fixed support plate 28 in the container 24 from above the fixed support plate, by way of example, by spraying from the spray-coating tube 70. Referring to Figure 9, a preselected cross-section or profile 166 of the initial liquid medium layer 164, in accordance with a design of the solid three-dimensional article being formed, then is solidified by the scanner head 54 applying the laser beam energy from the laser 50 to the liquid medium layer under the direction of a computer 168 (Figure 16). After the

preselected cross-section 166 of the liquid medium layer 164 has been solidified, the scanning mechanism 32, including the scanner head 54-coating mechanism 34, is moved vertically an increment corresponding to the thickness of the next layer to be solidified, (e.g., 0.0017" to 0.020") as illustrated by the phantom line in Figure 9.

Referring to Figures 1 and 10, the fluid inlet valve 154 (Figure 1) to the bellows 150 then is opened under the direction of the computer 168, to cause an initial incremental expansion of the bellows, to raise the level of the liquid medium 26 in the container 24 upward through the apertures in the article support plate 28, the preselected increment (e.g., 0.0017" to .020") above the previously solidified article cross-section 166, so that the surface tension of the thus-formed elevated layer 170 of the liquid medium 26 forms a meniscus 172 around the perimeter of the previously solidified article cross-section, without the liquid medium flowing over the upper surface of the solidified cross-section. Referring to Figure 11, the upper surface of the initial solidified cross-section 166 of the article then is spray-coated by the spray tube 70 from above the fixed support 28 in the container 24, to fill the recess formed by the meniscus 172 above the upper surface of the solidified article cross-section, with an additional layer 174 of the liquid medium 26. The spraying operation causes the meniscus 172 surrounding the article cross-section 166 to break, whereby the layers 170 and 174 of liquid medium 26 merge, as illustrated in Figure 12, thus completing the raising of the liquid level in the container 24 by a one-layer increment. With reference to Figure 13, the scanner head 54 then is again operated to solidify another preselected cross-section or profile 176 of the article 22 being

formed, under the direction of the computer 168, to form the next layer of the article. The liquid medium level raising step, liquid medium coating-and-meniscus breaking step, liquid medium solidifying step and scanner head-coating mechanism raising step, as represented by the steps 4, 5, 6, 7 and 8, and depicted in Figures 10, 11, 12 and 13, then are repeated, as necessary, until formation of the article 22 is completed.

In coating each of the solidified layers 166 and 176 of the liquid medium 26, it has been found that overspray of the liquid medium beyond the meniscus 172 onto the existing liquid medium, generally does not appear to produce a significant tolerance error in the finished article 22. While the reasons for this are not fully understood, it is believed to be due, at least in part, to the thinness of the liquid medium layers 166 and 176 involved. However, where tolerance variations are found to be a problem in any particular instance, a modified spray tube, as shown in Figures 5C and 5D may be used. In this embodiment, each spray aperture 108 is provided with a separate control pin 177 operated by a solenoid 178. Thus, by programming the computer 168 to control the solenoids 178 so that the spray tube 70 or 70' begins spraying only at one extreme end portion of a meniscus, sprays only those areas within the confines of the meniscus during travel of the spray tube, and stops spraying at an opposite extreme end portion of the meniscus, closer tolerances can be obtained. The coating tube 70 or 70' of Figures 6, 7A and 7B may be used in a similar manner by dividing the inner cylinder 116 into relatively movable sections and providing each section with a respective control solenoid 120.

Figure 15 discloses an optic system 178 which may be used in practicing the invention. The laser beam of the

laser 50 is directed through an RF acousto-optic beam modulator 180 in the form of a rotatable piezoelectric crystal which splits the beam into several orders of magnitude and which can be used as a beam shutter in a known manner. More specifically, when the modulator 180 is de-energized, the laser beam of the laser 50, which may pass from the modulator through a suitable bending mirror (not shown), strikes a portion of a blocking member 184 in a manner not illustrated. When the modulator 180 then is energized by an RF signal from an RF generator (not shown), the crystal splits the beam into several orders of magnitude, the zero, second and third orders of which still strike the blocking member 184, as illustrated in Figure 15. A first order beam , however, having an intensity on the order of 85% of the laser output, then passes through an aperture 182 in the blocking member 184 to a series of three (or more) bending mirrors 186, 188 and 190, and through an adjustably movable Z-axis correction focusing lens 192 on a reciprocal carriage 194, and an objective lens 196, to X and Y scanning mirrors 198 of the scanner head 54, which direct the beam so that it scans across the layer of liquid medium to be solidified. For this purpose, the correction lens 192 is focused so that a preselected diameter of the laser beam impinges upon the liquid medium layer, and the computer 168 is programmed to vary the position of the carriage 194, and thus the focusing lens 192, by a suitable servosystem (axis motor/encoder) 200, "on the fly", during the solidification operation, so that the impinging diameter of the laser beam remains constant as the beam is directed toward the liquid medium at a direction other than perpendicular, as for example, disclosed in U.S. Patents Nos. 4,797,749 and 4,816,920 of D.R. Paulsen, and assigned to General Scanning, Inc., of

Watertown Mass.

Referring to the block diagram of Figure 16, it is seen that apparatus for practicing the invention includes a CAD station 202 which is connected by an ethernet network to the control computer 168 in a known manner. The computer 168 is connected through a scanner controller 204 to a scanner head access system 206 including an axis motor/encoder 208, the Z-axis galvanometer 192, the X and Y mirrors 198 of the scanner head 54, and the focusing assembly 194. The computer 168 is also connected to the applicator motor/encoder 90, for the liquid medium applicator (coater mechanism) 34, through a motor/encoder interface 210 having a 3-axis motor driver 211 connected thereto, and is also connected to the focus servosystem (axis motor/encoder) 200, and scanner axis motor/encoder 208. The solenoid valve 154 for controlling fluid input to the bellows 150, and the drain valve 158 for the bellows, also are controlled by the computer 168 through a computer I/O interface 212, with safety interlocks 214 (e.g., open door, etc.) also connected to the computer 168 through the computer I/O interface.

With further reference to Figure 16, the laser 50 is connected to an associated power supply 216, in turn connected to a control panel 218 in a known manner. The beam of the laser 50 is directed therefrom to the beam modulator 180 having a linear and rotary micrometer adjustment system 219 and a mechanical safety shutter 220. The micrometer adjustment system 219 of the beam modulator 180 is utilized to select and direct the first order portion of the laser beam to the first bending mirror 186, as shown in Figure 15 and previously described, from which the laser beam passes to the second and third bending mirrors 188 and 190, and then to the Z-

axis galvanometer 192 of the focusing assembly 194, and to the scanner head X, Y mirrors 198 for a scanning (liquid medium solidifying) operation. The laser beam modulator 180 also is connected to a modulator amplifier 222 which receives signals from the scanner controller 204.

The control equipment as disclosed in Figure 16 is of a type which is generally known in the art. For example, the computer 168 may be the model "Smart Micro 386/120" or "Smart Micro 486/120" available from Microsmart, Inc. of Ashland, Mass. The CAD station 202 may be obtained from Sun Microsystems of Mountain View California, under the trademark "Sparkstation", and software may be obtained from Structure Dynamics Research Corporation of Cincinnati, Ohio as their "Ideas for Design". Similarly, the laser 50 may be the 5 watt argon-ion laser sold by Coherent, Inc. of Mountain View, California as their model "I-70" (a visible light laser); the scanner head 54 may be obtained from General Scanning, Inc. of Watertown, Mass.; the laser sensor 36 may be that sold by Namco Controls of Mentor, Ohio, under the trademark "Lasernet®"; and the RF beam modulator 189 may be the Model No. N30085-30 available from Newport Electro-Optics Systems of Melbourne, Florida.

The liquid medium 26 may be of any suitable type capable of being solidified when subjected to energy, such as a laser beam. For example, the liquid medium may be a UV polymer acrolite thermoset photosensitive plastic resin, such as that available from DSM Desotech, Inc. (formerly DeSoto, Inc.) of Chicago, Illinois under the trademark "Desolite®", or a suitable ceramic liquid. However, it has been found preferable to use as the liquid medium a polymer resin sensitive to visible laser light (e.g., 400 to 700nm), which is also available from

DSM Desotech Inc. as their composition No. 4057-16. The use of a visible light photo-hardenable polymer in combination with a visible light laser provides significant advantages over other systems, for example, employing a UV light laser. The reason for this is believed to be that visible light lasers generally provide more energy and thus are able to achieve better solidification and definition in the hardened layer, more quickly. Other suitable materials, however, may also be apparent to those skilled in the art.

Figure 17 is a flow chart of a sequence of operations of the apparatus 20 in accordance with the invention, in the forming of a solid three-dimensional article 22 from the liquid medium 26. At the beginning of a forming operation, the apparatus 20 proceeds through an initialization sequence, in which the computer 168 determines the then-existing position settings of the various units of the apparatus, applies power to all units, returns the units to their "home" positions, and calibrates the scanner system 32. (In the alternative, the units may be returned to their "home" positions manually by operation of a key on a keyboard (not shown) of the computer 168.) The computer 168 then displays the various available menu options and the operator selects one of the options. If the input option is not automatic, the operator then executes the desired manual command, such as "jog the scanner head up", whereupon, unless the command is an "exit" command, the computer 168 displays another input option for selection by the operator. If the command is an "exit" command, the computer 168 stores the positions of the various units of the system for the next operation, and the apparatus 20 is turned off.

If the input option selected by the operator is automatic, the computer 168 enters an automatic file name (e.g., the name of an article 22 to be formed) for processing. If the next cross-section or profile of the article 22 to be formed is other than the last cross-section, that is, the end of the file, the computer 168 then inputs information for the cross-section to be formed, and transfers the data to the scanning system 32. If a layer of the liquid medium 26 has been coated in a solidifying operation, the safety shutter 56 beneath the horizontal plate of scanning system 32 is opened and the cross-section of the article to be formed is scanned and solidified by the scanning system. After solidification of the cross-section has been completed and the safety shutter 56 has been closed, the scanning system 32 is raised one increment by the lift mechanism 44, and the bellows 150 is operated to expand an additional increment to raise the liquid medium level a desired amount, as sensed by the liquid medium level sensor 36, to form a meniscus 172 around the just-solidified profile as illustrated in Figure 10. If the liquid medium level sensor 36 does not operate, the bellows 150 is again operated an additional increment until operation of the liquid medium sensor occurs. The status of the forming operation, i.e., that the cross-section has been formed and that the system is ready to form the next cross-section, then is recorded in the computer 168, and the sequence of operations is repeated.

However, if the computer 168 determines that the last sequence of operations was the last cross-section for the article 22 being formed, i.e., the end of the file, the scanner system 32 is raised upward to its upper "home" position by the lift mechanism 44, and the drain valve 158 of the bellows 150 is opened by the computer 168 to

permit the liquid medium 26 in the container 24 to be lowered to its "home" position, to permit access to the completed article 22 and removal thereof from the apertured support plate 28 in the container 24, as well as removal and/or cleaning of the support plate for the next article forming operation. The removed article 22, while of relatively rigid construction, then is subjected to final curing under one or more lamps at a post-curing station, not shown, in a known manner.

Referring to Figures 19-24, the structure and operation of the second embodiment of the invention is similar to that of the first embodiment of the invention, as illustrated in Figures 1-14. However, in this more preferred embodiment of the invention, a first liquid medium layer 164" (Figures 20-22), and each subsequent liquid medium layer 170", 174" (Figure 22), is formed above an apertured fixed support plate member 28" entirely from above the fixed support and across the entire width of a container 24", by a liquid medium coating or dispensing mechanism 34".

With further reference to Figure 19, an apparatus 20" includes a vertically movable energy scanning mechanism or system 32" for solidifying successive preselected cross-sections of a liquid medium 26", to form an article 22" (shown in Figure 24), and the liquid medium coating mechanism 34" is mounted on the vertically movable scanning mechanism. A liquid medium metering device 40" is provided adjacent the bottom of a lower liquid medium storage container 25" (which corresponds to the liquid medium container sump portion 25 of the single container 24 in the first embodiment of the invention). The metering device 40" may be in the form of the withdrawal-and-feeding mechanism 40 of the first embodiment of the invention and comprising parts corresponding to the parts

128-148 thereof, but preferably is a digital metering pump, such as that available from IVEK® of Springfield, Vermont as their "Digispense" Pump No. 130.8.

The vertically movable scanning mechanism 32" comprises a horizontal support plate 42" which is connected to a vertical traversing mechanism (not shown in Figures 19-24), such as the mechanism 44 in Figure 1, for raising and lowering the scanning mechanism. Similarly, as is shown in Figure 19, a source of energy, such as a laser 50", a laser beam focusing optic system 52" and a scanner head 54", for directing the laser beam energy to solidify successive layers of the liquid medium 26", are also mounted on the support plate 42" in a suitable manner, as in the first embodiment of the invention.

In general, the liquid medium coating mechanism 34" may comprise a sub-frame 58" mounted beneath the horizontal support plate 42", with a liquid medium spray or dispensing tube 70" mounted on the subframe and extending across the width of the container 24", as shown in Figure 19. The dispensing tube 70" is supported on the subframe 58" for reciprocable traversing movement from adjacent one side of the container 24" to the other, as illustrated in Figures 20 and 22, for forming the sequential layers of the liquid medium in the container above the fixed support 28". The liquid medium 26" is fed into the dispensing tube 70" by the resin metering device 40", from the lower liquid medium storage container 25" via a flexible line 80".

With further reference to Figure 19, as in the first embodiment of the invention, the laser beam from the laser 50" passes through a beam modulator 180", which may be used in conjunction with a blocking member 184", as a shutter, as previously described. Thus, when the beam

modulator 180" is energized (by an RF signal from an RF generator, not shown), a first order portion of the laser beam passes to bending mirrors 186" and 188", and then to a bending mirror 190" of the scanning mechanism 32". Within the scanning mechanism 32", the laser beam then passes through an adjustably movable Z-axis correction focusing lens 192" on a reciprocal carriage 194", with the focusing lens and carriage being moved by a suitable servosystem 200", "on the fly", during a solidification operation, so that the impinging diameter of the laser beam remains constant as the beam is directed toward a layer of the liquid medium 26" at a direction other than perpendicular. The laser beam then passes through an objective lens 196", to X and Y scanning mirrors 198" of the scanner head 54", which direct the beam so that it is traversed across the layer of liquid medium 26" to be solidified.

Referring now to Figure 20, this figure shows the central portion of the apparatus 20" turned 90° from the showing in Figure 19, so that the front of the apparatus is at the left and the back of the apparatus is at the right in this figure. At the beginning of a laser modeling operation, a sufficient amount of the liquid medium 26" is withdrawn from the container 25" and introduced, via the flexible line 80" and the dispensing tube 70", into the container 24" to fill the lower portion of the container and the apertures in the fixed support plate 28" up to the top of the support plate. Preferably, the liquid medium 26" is introduced, for example, at the center and adjacent opposite ends of the dispensing tube 70", for more uniform liquid medium distribution. As viewed in Figure 20, the elongated dispensing tube 70" then is traversed from the left-hand side (front) of the container 24", to the right-hand side

(back) of the container, as illustrated by the horizontal arrows, while the resin metering device 40" feeds a preselected amount of the liquid medium 26" from the storage container 25", to form a first liquid medium layer 164" (thickness exaggerated for purposes of illustration) above the fixed support plate 28". As viewed in Figure 21, with the dispensing tube 70" then stopped adjacent the back of the container 24", a preselected cross-section of the initial layer 164" is solidified by the laser beam from the laser 50" (shown only in Figure 19).

As is illustrated in Figure 22 by the vertical arrow, the support plate 42" then is raised vertically so that the parts mounted thereon, comprising the laser 50" (Figure 19), scanning mechanism 32" and coating mechanism 34", including the dispensing tube 70", are raised a one layer increment for a next liquid medium dispensing-and-solidifying operation.

Next, referring to Figure 23, the dispensing tube 70" is traversed from the back of the container 24", in a reverse direction (to the left in this figure) to its initial front position, while the resin metering device 40" again delivers a preselected amount of the liquid medium 26" to the dispensing tube, to form a second liquid medium layer 170", 174" (thickness also exaggerated for purposes of illustration) above the initial layer 164" and over the first-solidified article cross-section 166". With the dispensing tube 70" then located adjacent the front of the container 24", as shown in Figure 23, a preselected cross-section of the second layer 170", 174" then is solidified by the laser beam as previously described. This procedure, of alternately dispensing a layer of the liquid medium 26" from the dispensing tube 70", solidifying a preselected cross-

section of each layer by the laser beam, and raising the scanning mechanism 32" and coating mechanism 34", including the dispensing tube and other associated structure,then is repeated, until the article 22" has been completed, as illustrated in Figure 24. The liquid medium 26" then may be drained from the container 24" by a pump (or valve) 158" into the lower liquid medium storage container 25", and the article 22" removed. In other respects, the apparatus functions essentially as shown in Figure 17 for the first embodiment of the invention, except that a determination that the level of the liquid medium is incorrect results in operation of the coating mechanism 34", rather than the bellows 150.

The liquid medium coating mechanism 34" may be of essentially the same construction as the liquid medium coating mechanism 34 shown in Figures 1-3 of the first embodiment of the invention, but preferably is of the modified type as disclosed in Figures 25-27. Figures 25-27 disclose a liquid medium coating mechanism 34''' which comprises a rectangular subframe 58''' and an apertured liquid medium coating or dispensing tube 70''' having a flexible feed line 80''' connected to a central portion and opposite end portions thereof. The dispensing tube 70''' is secured adjacent opposite ends to lower ends of vertically extending support rods 222 secured at upper ends to respective driven slide blocks 224. The slide blocks 224 are supported for sliding movement on horizontally disposed slide rods 226 having opposite ends fixedly mounted in respective ones of a pair of opposite walls of the subframe 58'''. The slide blocks 226 are driven by a twin linear ball screw drive mechanism 228 comprising a pair of rotatable drive screws 230 which are threadably received in associated ball screw members 232 mounted in respective ones of the slide blocks, with

opposed ends of the drive screws journaled in the opposed walls of the subframe 58'''. A projecting portion of each drive screw 230 has a drive pulley 82''' fixedly mounted thereon and drivingly connected by a belt 84''' to a drive pulley 86''' on a shaft of a small reversible drive motor 90''' mounted on a projecting portion of the subframe 58'''.

Referring to Figures 26 and 27, the bottom of the liquid medium dispensing tube 70''' includes a plurality of small apertures 108''' through which the liquid medium 26''' (shown only in Figure 27) is forced under pressure, such as by the liquid medium metering device 40" of Figures 19-24, in the forming of a layer of the liquid medium. The size of the apertures 108''' is such that when pressure exerted by the liquid medium metering device 40" is interrupted, as previously described, the flow of the liquid medium 26''' through the apertures also is automatically interrupted, thus eliminating the need for any solenoid-operated shut-off mechanisms as previously described and shown in Figures 5C and 5D. By way of example, while the number and size of the apertures 108''' may vary depending on other process variables, such as the thickness of the layer to be formed, and the viscosity of the liquid medium 26''', in general, favorable results have been achieved in the forming of a liquid medium layer in the abovementioned range on the order of 0.0017" to 0.020" thick, using three rows of apertures spaced apart in a range on the order of 0.055" to 0.065", with the apertures in each row spaced apart in a range on the order of 0.090" to 0.105", and with an aperture size in a range on the order of 0.010" to 0.20".

Figure 27 illustrates the use of the liquid medium dispensing tube 70''' of Figures 25 and 26 in the forming

of a layer 170''', 174''' of the liquid medium 26'''. For this purpose, the dispensing tube 70''' is located above a previously formed liquid medium layer 164''' a distance D slightly greater than the thickness of the layer 170''', 174''' being formed, so that the liquid medium 26''' is dispensed in a uniform, controlled manner as a result of capillary action and the surface tension of the liquid medium, as the liquid medium is dispensed onto the previous layer. More specifically, with the dispensing tube 70''' disclosed, the liquid medium 26''' is dispensed in the form of three rows of capillary columns to form a series of three sublayers of essentially uniform thickness, with the surface tension of the sublayers becoming broken as the sublayers engage one another, to form the unitary liquid medium layer 170''', 174''' to the desired thickness. While the distance D between the bottom of the dispensing tube 70''' and the previously formed layer 164''' may vary depending upon other process variables, such as the thickness of the layer 170''', 174''' being formed, for a layer thickness in the abovementioned range of 0.0017" to 0.020", favorable results have been achieved with the distance D in a range on the order of 0.025" to 0.035".

Figure 28 is a schematic diagram illustrating a path which may be travelled by a laser beam LB in the solidification of the cross-section of a liquid medium layer L. In this instance, the layer L is illustrated as being of a cylindrical configuration, having an outer periphery OP and an inner periphery IP. To define the outer periphery OP of the layer L, the laser beam LB is directed so that the center of the beam travels along a circular path indicated by a broken line P1 spaced radially inward a distance equal to one-half the beam diameter. Similarly, the inner periphery IP of the layer

L is defined by directing the laser beam LB so that the center of the beam travels along a circular path designated by a broken line P2 spaced radially outward from the inner periphery IP a distance equal to one-half the beam diameter. The remaining portion of the layer L is solidified by traversing the laser beam LB back and forth across the layer, as illustrated by solid lines P3, with each path of the laser beam overlapping a previous path, such as by one-half of the beam diameter. At the same time, the travel of the laser beam LB in either direction is terminated short of the outer and inner peripheries OP and IP of the layer L, such as by one-half the beam diameter, so that the traversing laser beam does not touch either the outer or inner periphery, so as to cause irregularities therein.

Further, in solidifying successive alternate ones of the liquid medium layers, the laser beam LB preferably is traversed in directions perpendicular to the paths P3 for the layer L to form a more uniform article structure. The layer periphery-defining paths P1 and P2 of the laser beam LB, and the layer inner portion-defining traversing paths P3 of the laser beam, also may be accomplished in any order, but preferably the outer and inner peripheries OP and IP of the layer L are defined after the layer inner portion traversing paths P3 have been completed. If desired, the size of the laser beam LB also may reduced in diameter for the purpose of defining the outer and inner peripheries OP and IP of the layer L.

Figures 29A and 29B illustrate a laser beam-offset mode of operation in accordance with the invention, wherein an article being formed includes a downwardly facing surface. For example, Figure 29A illustrates an inverted L-shaped article A on an apertured fixed support plate P, having a vertically extending portion V and a

laterally projecting cantilevered portion C at its upper end, with the cantilevered portion having a downwardly facing surface S. Thus, if in the initial forming of the cantilevered portion C, a laser beam LB is directed at a surface of a liquid medium (not shown) corresponding to the downwardly facing surface S, the laser beam actually will penetrate the liquid medium to a level below the surface a distance d as indicated by a broken line L1, thereby causing an error in the configuration of the formed article A. Accordingly, in forming the surface S of the article cantilevered portion C, the laser beam LB is programmed so that it is not directed across the liquid medium above the surface until the level of the liquid medium is at a corresponding distance d above the level of the surface, as indicated by the broken line L2.

Similarly, Figure 29B illustrates the forming of a block-shaped article A' having a central opening O therethrough, with the opening having an interior downwardly facing surface S'. Accordingly, as in the article A shown in Figure 29A, in forming of the surface S' of the opening O, if a laser beam LB' is directed to successive surface levels of a liquid medium (not shown) at points corresponding to the downwardly facing surface, because of the solidification depth penetration d' of the laser beam, the upper half of the opening will be solidified along a broken line L1', producing an error in the configuration of the formed article A'. Accordingly, as in Figure 29A, in forming the downwardly facing surface S' of the opening O, the laser beam LB' is programmed so that it is directed at points on successive surface levels of the liquid medium which are the distance d' above the surface S', as illustrated by the broken line L2'.

Figure 30A shows an article A having one or more compound and/or reverse curved peripheral surfaces S, and Figure 30B is a view of a coordinate network for a portion of one of the curved compound curved surfaces, made up of coordinates C, which may be developed utilizing the abovementioned software of the Structure Dynamics Research Corporation. While the coordinates C are shown in the form of a grid which will define square-shaped facets on the surfaces S of the finished article A, other grid arrangements, such as triangular, rectangular or polygonal, may be used.

With reference to Figure 30C, which represents a cross-sectional layer L of the article A, in utilizing the thus-defined network of Figure 30B in forming the compound and/or reverse curved surfaces S of the article, in the past a laser beam has been directed around the periphery of the layer between successive ones of the coordinates C along straight-line paths SP. As a result, a thus-formed peripheral portion of the layer L, instead of being a true curve or series of curves, is in the form of a series of the interconnected straight-line paths SP, and the resultant curved surfaces S actually are a series of essentially flat-faced facets. This can be partially remedied by moving the coordinates C closer together, but this is disadvantageous for various reasons, such as the additional coordinate computations and coordinate memory storage required.

Accordingly, referring to Figure 30D, in accordance with the subject invention, instead of moving coordinates C' for an article layer L' of an article A' closer together, the coordinates are selectively moved further apart, depending upon the sharpness of the curves being formed. The computer 168 then is programmed with artificial curve coordinate data, corresponding to a

desired curve portion CP between each successive pair of the coordinates C', which has been generated by suitable software interpolation using various criteria stored in the CAD station 202, such as the known positions of each successive pair of the coordinates C', positions of the coordinates in adjacent article layers, and radii of curvature between coordinates. During the solidifying of the article A', the computer 168 then directs the laser beam in short straight-line or curved paths along the artificially created curved paths CP, to form the article A' with essentially smooth flowing curved surfaces S'.

In summary, a new and improved method of and apparatus for forming a solid three-dimensional article 22, such as the articles 22a and 22b in Figures 18A and 18B, respectively, or the article 22" in Figure 24, from a liquid medium 26, has been disclosed. The method and apparatus, as disclosed in the first preferred embodiment of the invention shown in Figures 1-14, involves initially coating a layer of the liquid medium 26 onto the apertured support plate 28 in the liquid medium container 24, as illustrated in Figure 8. An initial cross-section or profile 166 of the article 22 then is formed by solidifying the liquid medium 26, as illustrated in Figure 9, and the scanner head 54 is raised one increment. Next, the liquid level of the liquid medium 26 is raised by operation of the bellows 150, to form the meniscus 172 around the solidified cross-section or profile 166 of the article 22, as illustrated in Figure 10. Another coating of the liquid medium 26 then is applied to the solidified cross-section or profile 166 of the article 22 within the recess defined by the meniscus 172, as shown in Figure 11, causing the meniscus to break and the liquid medium layers 170 and 174 to merge, as shown in Figure 12. A

next cross-section or profile 176 of the article 22 then is solidified by the scanning system 32, as illustrated in Figure 13, and the scanner head 54 is again raised an additional increment. This sequence of operations then is continued until all of the cross-sections or profiles of the article 22 being formed have been completed. The scanning system 32 then may be raised to its upper "home" position by the lift mechanism 44, and the drain valve 158 for the bellows 150 opened to permit lowering of the liquid medium 26 in the container 24 to its lowermost "home" position, to permit access to the completed article 22 and removal of the article from the apparatus 20.

In the second preferred embodiment of the invention, as shown in Figures 19-24, which operates in essentially the same manner as the first embodiment of the invention, each layer of the liquid medium 26" is produced above the apertured fixed support plate 28" by dispensing the entire layer from the dispensing tube 70" in the container 24". Further, when the dispensing tube 70''' shown in Figures 25-27 is utilized, the small size of the dispensing apertures 108''' causes the tube to stop dispensing automatically in response to cessation of exerted pressure by the liquid medium metering device 40", without the use of any other type shut-off mechanism. The traversing of the dispensing tube 70''' closely adjacent each previous liquid medium layer also enables the liquid medium 26''' to be dispensed in a uniform, controlled manner as a result of capillary action and surface tension.

As stated previously, the laser 50 is preferably a visible light laser and the liquid polymer 26 is one which hardens by such laser energy. Other type lasers can be substituted for the visible light laser without

departing from the invention, such as a UV light laser, a Nd-Yag laser or a CO_2 laser, along with a compatible polymer. Other known types of energy sources, such as other forms of UV or visible light, invisible light, cathode ray tubes, electron beams, x-rays and other forms of radiation and/or high energy beams may also be used in this invention. However, it is believed that a visible light laser is the preferred energy source because visible light lasers generally provide more energy and thus are able to achieve better solidification and definition in the hardened layer, more quickly.

It is to be understood that the foregoing description and accompanying drawings set forth the preferred embodiments of the invention at the present time. Various modifications, additions and alternative designs will, of course, become apparent to those skilled in the art in light of the foregoing teachings without departing from the spirit and scope of the disclosed invention. Therefore, it should be appreciated that the invention is not limited to the disclosed embodiments but may be practiced within the full scope of the appended claims.

WHAT IS CLAIMED IS:

1. A method of forming a solid three-dimensional article from a liquid medium capable of solidification when subjected to prescribed energy, which comprises the steps of:

providing a fixed support in a container for holding a liquid medium;

producing a layer of the liquid medium in the container above the fixed support;

solidifying a preselected cross-section of such layer by exposing at least a portion of the layer to prescribed energy in accordance with a design for the three-dimensional article; and

alternately repeating the liquid medium layer-producing and solidifying steps, as necessary, to form the solid three-dimensional article.

2. The method as recited in claim 1, wherein the liquid medium layers are produced by dispensing at least a portion of each layer from above the fixed support in the container.

3. The method as recited in claim 2, wherein the dispensing of the portions of the liquid medium layers from above the fixed support in the container, includes traversing a dispensing mechanism between opposite sides of the container.

4. The method as recited in claim 1, wherein the liquid medium layers are produced by raising the level of the liquid medium relative to the fixed support in the container.

5. The method as recited in claim 4, wherein the liquid medium layers are produced by dispensing at least a portion of each layer from above the fixed support in the container.

6. The method as recited in claim 4, wherein raising the level of the liquid medium in the container includes the steps of:

forming a meniscus around the periphery of a previously solidified cross-sectional portion of the article to produce a portion of the respective layer of the liquid medium; and

then producing the remainder of the layer by dispensing liquid medium onto the previously solidified cross-sectional portion from above the fixed support in the container, so that the meniscus is broken and the liquid medium forms an essentially level surface.

7. The method as recited in claim 1, wherein each of the liquid medium layers is produced by dispensing the entire layer from above the fixed support in the container.

8. The method as recited in claim 1, wherein the solidifying steps are performed with a laser at a UV frequency.

9. The method as recited in claim 1, wherein the solidifying steps are performed with a laser at a visible light frequency.

10. The method as recited in claim 2, which comprises the additional step of raising a dispensing mechanism for producing the dispensed portions of the liquid medium layers, a distance corresponding to a thickness of each layer after production of the layer.

11. The method as recited in claim 1, which comprises the additional step of raising an energy source for solidifying the preselected cross-section of each layer of the liquid medium, a distance corresponding to a thickness of each solidified cross-section after solidification of the cross-section.

12. The method as recited in claim 11, wherein the energy source is a laser and the liquid medium layers are produced by dispensing at least a portion of each layer from a dispensing mechanism above the fixed support in the container, and which also comprises raising the dispensing mechanism a distance corresponding to a thickness of each layer after production of the layer.

13. The method as recited in claim 12, wherein the energy source and the dispensing mechanism are raised simultaneously.

14. The method as recited in claim 1, wherein the solidifying of the portions of the liquid medium comprises controlling a laser beam by applying an RF signal to an acousto-optic modulator to cause at least a portion of the laser beam to be deflected from a blocked position to an unblocked liquid medium solidifying portion.

15. The method is recited in claim 2, wherein the dispensed liquid medium is dispensed under pressure from an apertured member through apertures of a size such that the liquid medium flows through the apertures only when pressure is applied to the liquid medium.

16. The method is recited in claim 15, wherein the apertures of the apertured member are located closely adjacent a previous layer of the liquid medium in a dispensing operation, such that the liquid medium is dispensed from the apertures in a uniform, controlled manner as a result of capillary action and surface tension.

17. The method is recited in claim 16, wherein the apertures have a diameter in a range on the order of 0.010" to 0.020" and are spaced from the previous layer of the liquid medium in a range on the order of 0.025" to 0.035".

18. The method as recited in claim 1, wherein the solidification of the cross-sections of the liquid medium layers further comprises the steps of:

directing a laser beam around the outer periphery, and any inner periphery, of each cross-section;

traversing the laser beam back and forth across each cross-section such that the laser beam path on each traverse overlaps the laser beam path on a previous traverse, and such that the laser beam paths do not engage the cross-section outer peripheries or any cross-section inner peripheries, with the laser beam being traversed across alternate ones of the cross-sections in directions essentially perpendicular to one another.

19. The method as recited in claim 1, wherein, in the solidification of a downwardly-facing surface of the article, a laser beam is directed to a surface of the liquid medium which is spaced above the downwardly facing surface to compensate for laser beam solidification depth penetration into the liquid medium.

20. The method as recited in claim 1, which further comprises the steps of:

producing a network of coordinates representing curved peripheral surfaces of the three-dimensional article;

generating by interpolation, based on the coordinate positions of each successive pair of the coordinates for each liquid medium layer, and other associated article data, artificial data defining a desired curved path between each of said pair of coordinates; and

directing an energy source along the generated curved paths so that the article is solidified with essentially smooth flowing, curved peripheral surfaces.

21. Apparatus for forming a solid three-dimensional article from a liquid medium capable of solidification when subjected to prescribed energy, which comprises:

container means for holding a supply of the liquid medium;

fixed support means in the container means, for supporting the solid three-dimensional article being formed;

means for producing a layer of the liquid medium in the container means above the fixed support means;

means for solidifying a preselected cross-section of such layer in accordance with a design for the three-dimensional article; and

means for alternately and repetitively operating said liquid medium layer-producing and solidifying means, as necessary, to form the solid three-dimensional article.

22. Apparatus as recited in claim 21, which further comprises means for dispensing at least a portion of each liquid medium layer from above the fixed support means in the container means.

23. Apparatus as recited in claim 21, wherein the layer-producing means raises the level of the liquid medium relative to the fixed support means in the container means, to produce each layer of the liquid medium.

24. Apparatus as recited in claim 23, wherein the layer-producing means includes means for dispensing at least a portion of each layer of the liquid medium from above the fixed support means in the container means.

25. Apparatus as recited in claim 23, wherein the layer-producing means includes:

means for raising the level of the liquid medium so as to form a meniscus around the periphery of a

previously solidified cross-sectional portion of the article, to form a portion of the respective layer of the liquid medium; and

means for dispensing liquid medium onto the previously solidified cross-sectional portion above the fixed support means in the container means to form the remainder of the layer and so that the meniscus is broken and the liquid medium forms an essentially level surface.

26. Apparatus as recited in claim 21, wherein the fixed support means is an apertured plate.

27. Apparatus as recited in claim 22, wherein the dispensing means dispenses each of the liquid medium layers in its entirety from above the fixed support means in the container means.

28. Apparatus as recited in claim 22, wherein the dispensing means includes an elongated apertured tube.

29. Apparatus as recited in claim 22, wherein the dispensing means comprises:

an outer elongated cylinder and an inner elongated cylinder mounted in relatively rotatable coaxial relationship, each cylinder including an elongated slot; and

means for causing relative rotation between the cylinders to cause relative movement of the elongated slots between a non-aligned closed position and an aligned dispensing position.

30. Apparatus as recited in claim 22, wherein the dispensing means is mounted for horizontal reciprocating movement above the support means.

31. Apparatus as recited in claim 30, which further comprises:

gear rack means for supporting the dispensing means for the horizontal reciprocating movement above the support means; and

drive means for reciprocating the dispensing means on the gear rack means.

32. Apparatus as recited in claim 30, which further comprises:

slide means for supporting the dispensing means for the horizontal reciprocating movement above the support means;

means for suspending the dispensing means from the slide means; and

drive screw means for reciprocating the slide means and the dispensing means.

33. Apparatus as recited in claim 22, wherein the dispensing means is mounted for oscillating swinging movement above the support means, and means are provided for oscillating the dispensing means.

34. Apparatus as recited in claim 22, wherein the dispensing means comprises:

means for dispensing the liquid medium under pressure; and

an apertured dispensing member having apertures of a size such that the liquid medium flows through the apertures only when pressure is applied to the liquid medium.

35. Apparatus as recited in claim 34, wherein the apertures of the dispensing member are located closely adjacent a previous layer of the liquid medium during a dispensing operation, such that the liquid medium is dispensed from the apertures in a uniform, controlled manner as a result of capillary action and surface tension.

36. Apparatus as recited in claim 35, wherein the dispensing member apertures have a diameter in a range on the order of 0.010" to 0.020" and are spaced from the previous layer of the liquid medium in a range on the

order of 0.025" to 0.035".

37. Apparatus as recited in claim 22, which further comprises:

means for withdrawing a portion of the liquid medium from a lower portion of the container means and feeding the withdrawn liquid medium to the dispensing means.

38. Apparatus as recited in claim 37, wherein the container means comprises:

an upper container in which the dispensing means is disposed;

a lower container from which the liquid medium is withdrawn and fed by the withdrawing-and-feeding means to the dispensing means; and

means for selectively causing the liquid medium in the upper container to flow back into the lower container.

39. Apparatus as recited in claim 37, wherein the liquid medium withdrawing-and-feeding means includes a double acting piston in a cylinder, and valve means for controlling flow of the liquid means to and from the piston and the cylinder.

40. Apparatus as recited in claim 37, wherein the liquid medium withdrawing-and-feeding means is a digital metering pump.

41. Apparatus as recited in claim 22, wherein at least one of the solidifying means and the dispensing means is mounted for vertical movement relative to the fixed support means in the container.

42. Apparatus as recited in claim 22, wherein the solidifying means and the dispensing means both are mounted for vertical movement relative to the fixed support means in the container.

43. Apparatus as recited in claim 42, which further comprises means for raising the solidifying means and the

dispensing means simultaneously.

44. Apparatus as recited in claim 22, wherein the dispensing means is a coating means.

45. Apparatus as recited in claim 51, wherein the liquid medium solidifying means includes a UV laser.

46. Apparatus as recited in claim 51, wherein the liquid medium solidifying means includes a visible light laser.

47. Apparatus as recited in claim 21, which further comprises:

a laser which produces a laser beam for solidifying the portions of the liquid medium; and

an acousto-optic modulator through which the laser beam normally passes to a blocking member, the acousto-optic modulator being responsive to an RF signal to cause at least a portion of the laser beam to be deflected to an unblocked position for solidifying the liquid medium.

48. Apparatus as recited in claim 21, which further comprises:

means for solidifying preselected cross-sections of successive layers of the liquid medium by directing a laser beam around the outer periphery, and any inner periphery, of each cross-section; and

means for traversing the laser beam back and forth across each cross-section such that the laser beam path on each traverse overlaps the laser beam path on a previous traverse, and such that the laser beam paths do not engage the cross-section outer peripheries or any cross-section inner peripheries, with the laser beam being traversed across alternate ones of the cross-sections in directions essentially perpendicular to one another.

49. Apparatus as recited in claim 21, wherein the article includes a downwardly-facing surface, and which further comprises:

means for directing a laser beam to a surface of the liquid medium which is spaced above the downwardly facing surface to compensate for laser beam solidification depth penetration into the liquid medium.

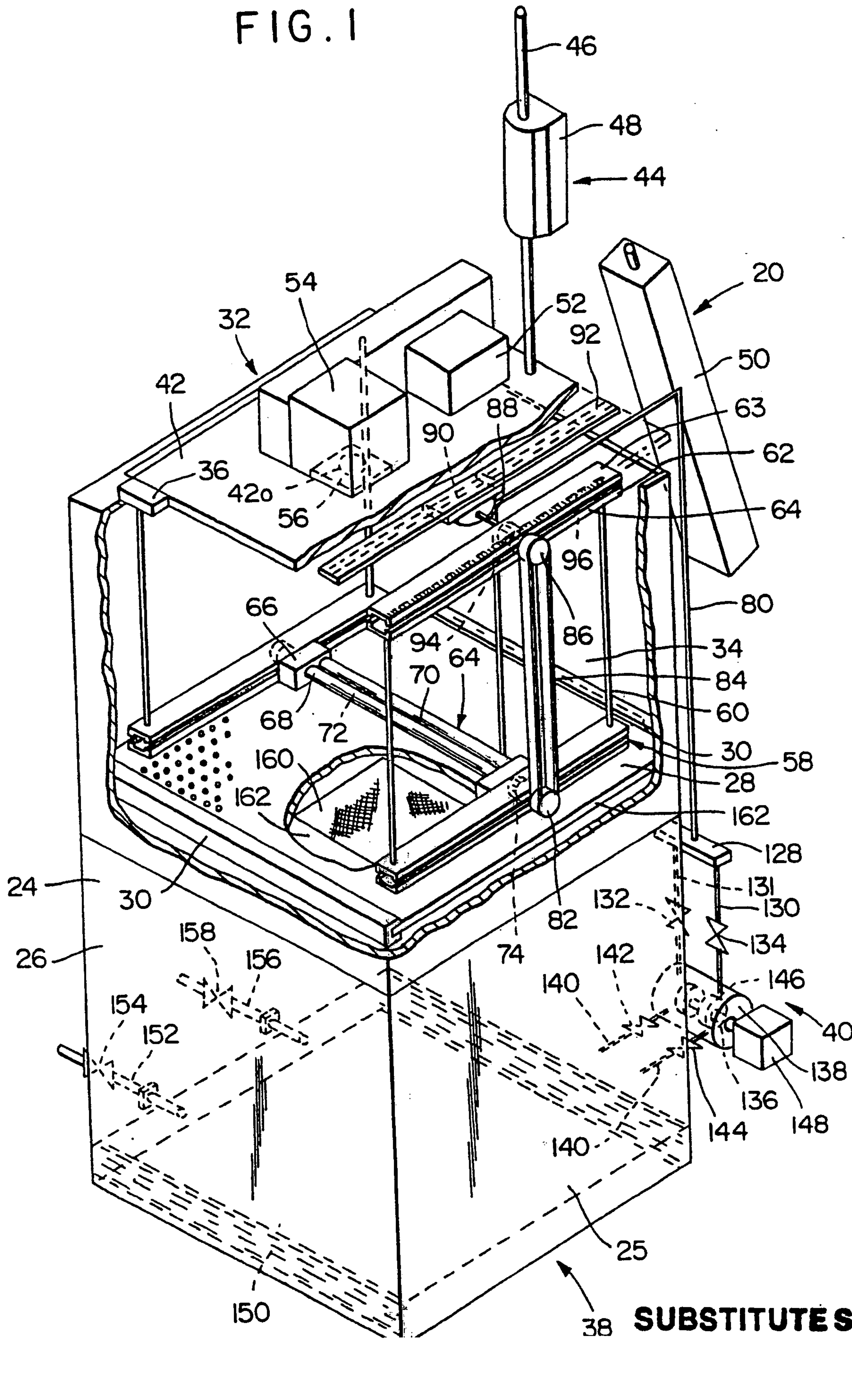
50. Apparatus as recited in claim 21, which further comprises:

means for producing a network of coordinates representing curved peripheral surfaces of the three-dimensional article;

means for generating, by interpolation, based on the coordinate positions of each successive pair of the coordinates for each liquid medium layer, and other associated article data, artificial data defining a desired curved path between said pair of coordinates; and

means for directing said solidifying means along the generated curved paths so that the article is solidified with essentially smooth flowing, curved peripheral surfaces.

FIG. 1


46
48
44
20
54
52
32
92
42
50
88
63
90
62
36
42o
56
64
96
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66
86
94
64
34
70
84
68
72
60
30
58
160
28
162
162
128
24
30
131
132
130
82
74
134
26
158
156
142
146
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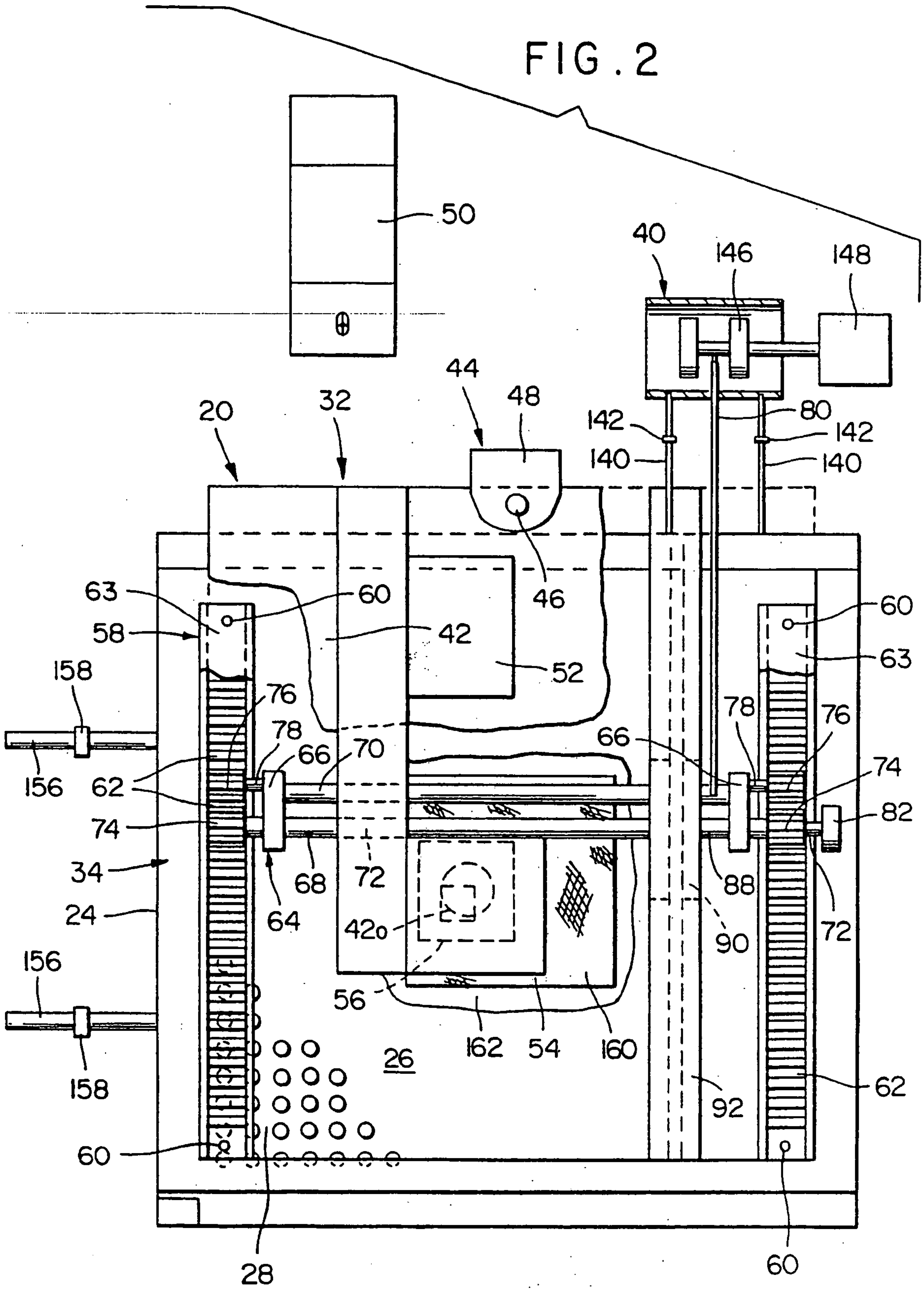
154
40
152
138
136
148
144
140
25
150
38

FIG. 2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40
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142
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142
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140
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42
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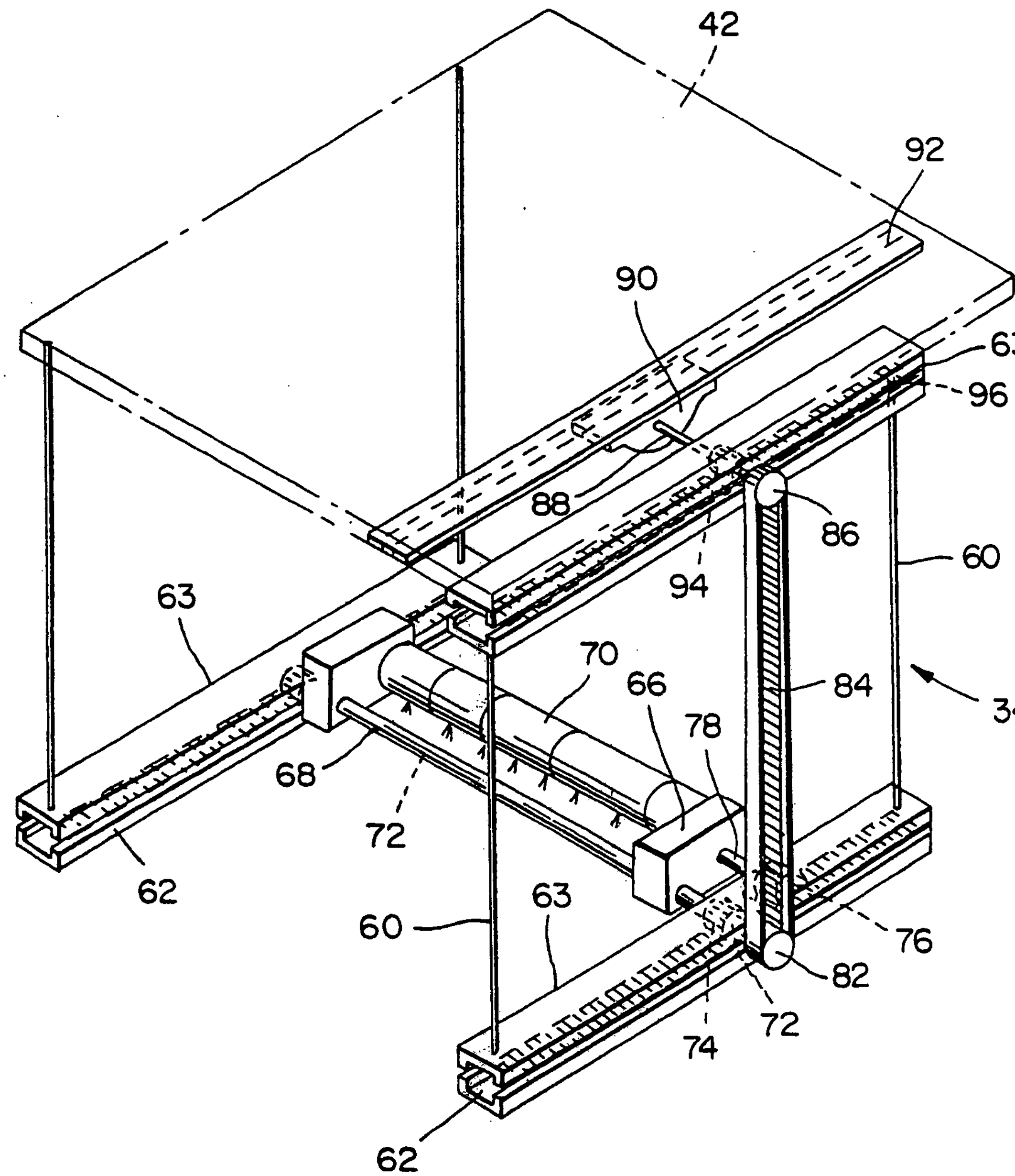
52
158
76
78
76
66
78
70
66
74
156
62
82
74
68
72
34
64
88
24
42o
90
72
156
56
162
54
160
26
92
62
158
60
28
60

FIG. 3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92
90
63
96
88
86
94
60
63
70
66
84
34
78
68
72
62
63
60
76
82
72
74
62

FIG. 4

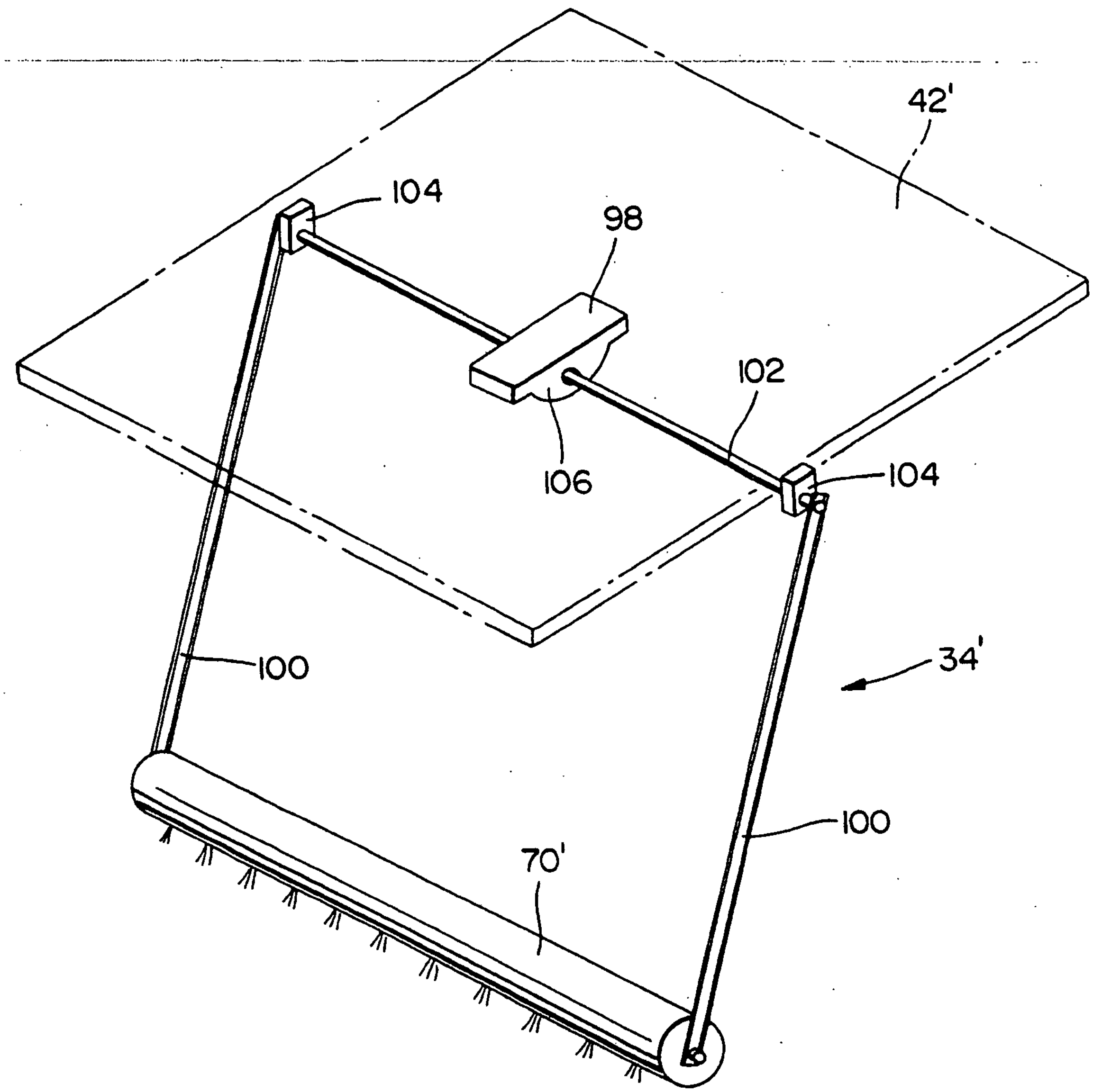


FIG. 5A

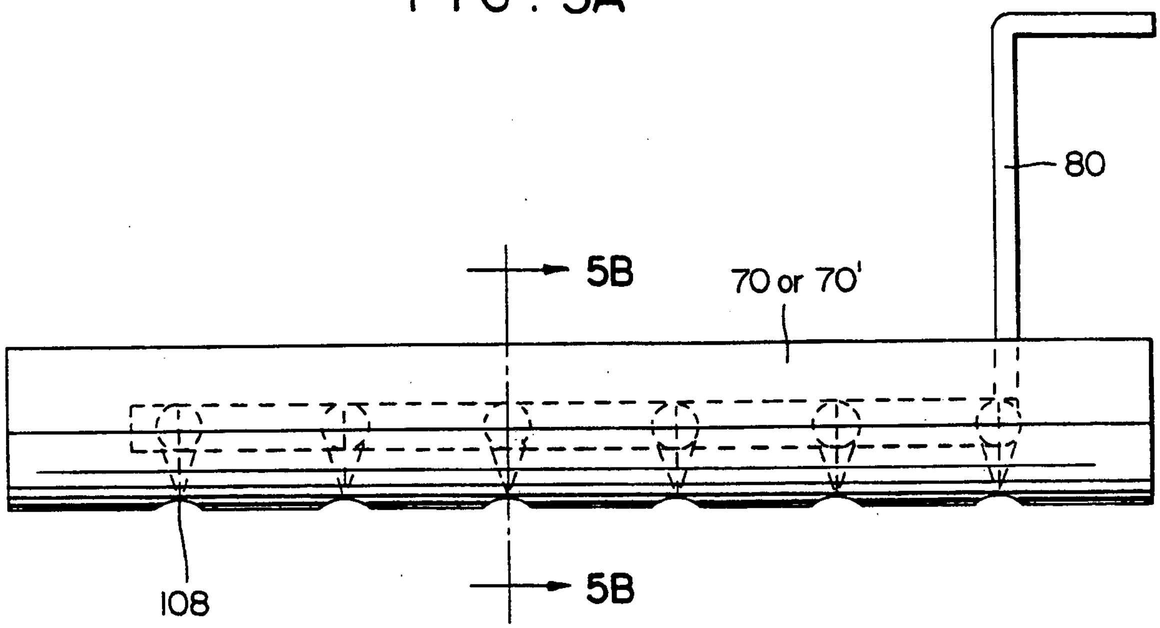


FIG. 5B

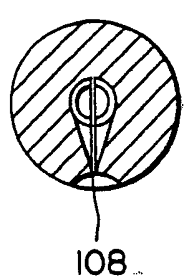


FIG. 5C

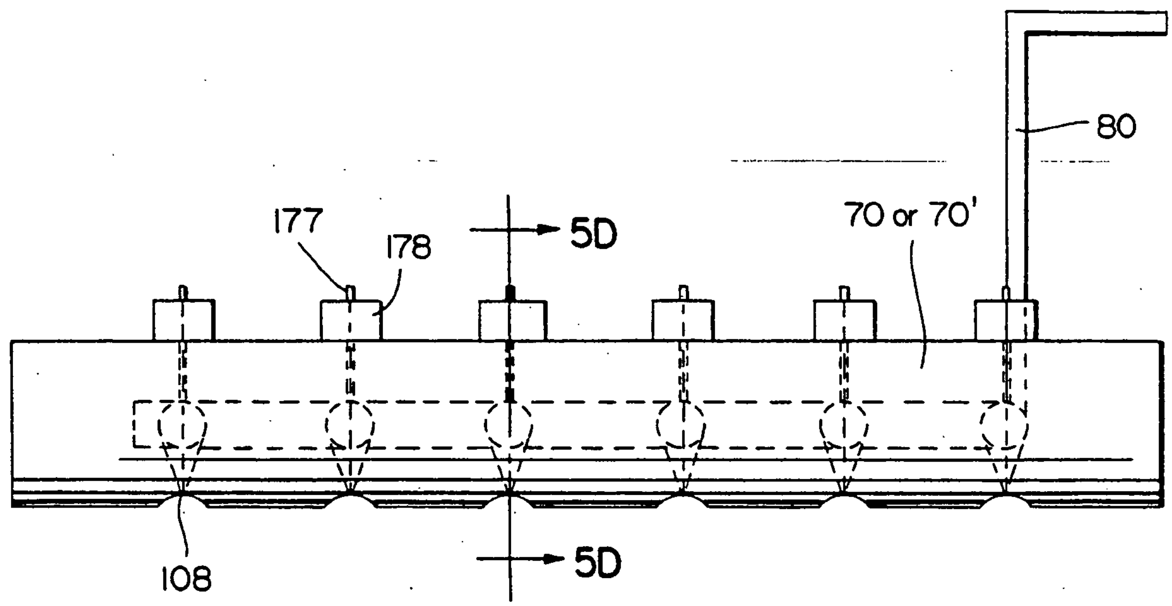


FIG. 5D

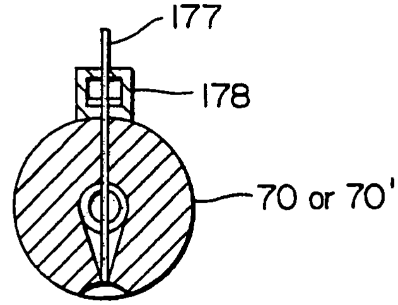


FIG. 6

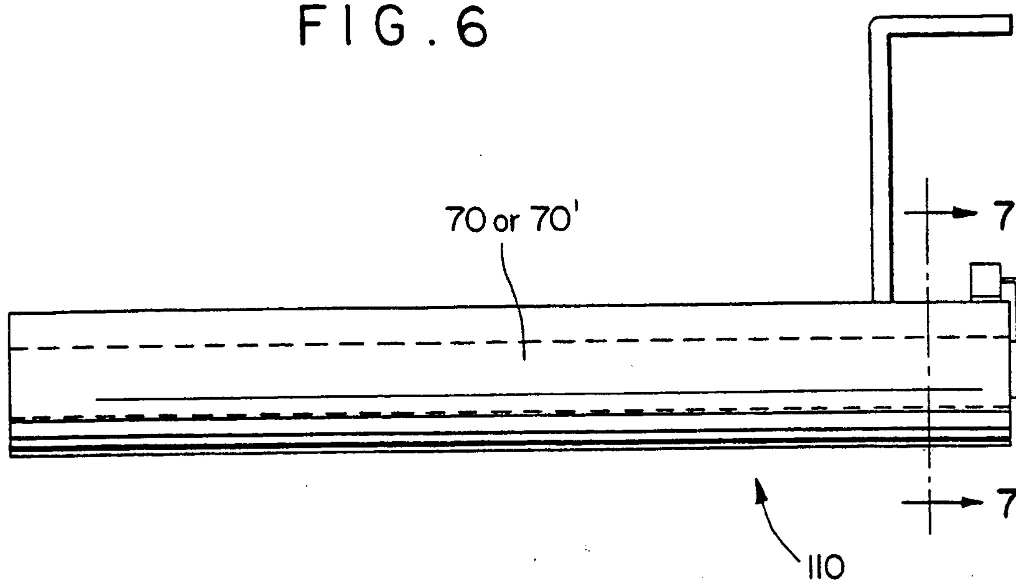


FIG. 7A

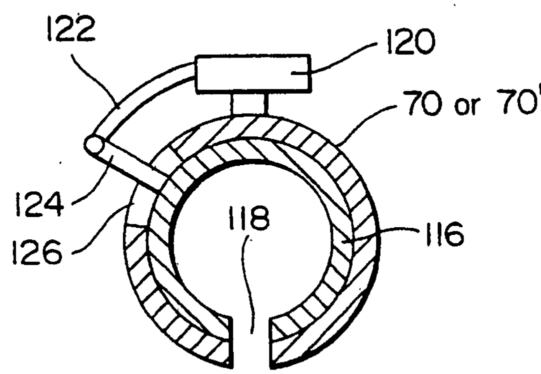
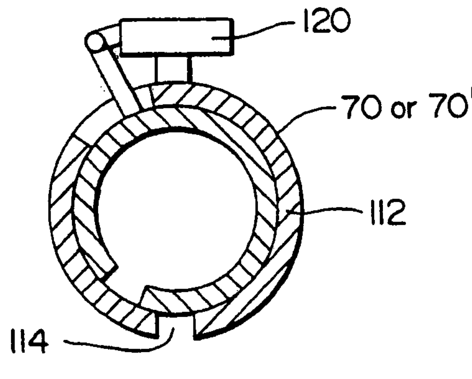


FIG. 7B



SUBSTITUTE SHEET

FIG. 8

STEP I

COAT FIRST LIQUID MEDIUM LAYER ON SUPPORT.

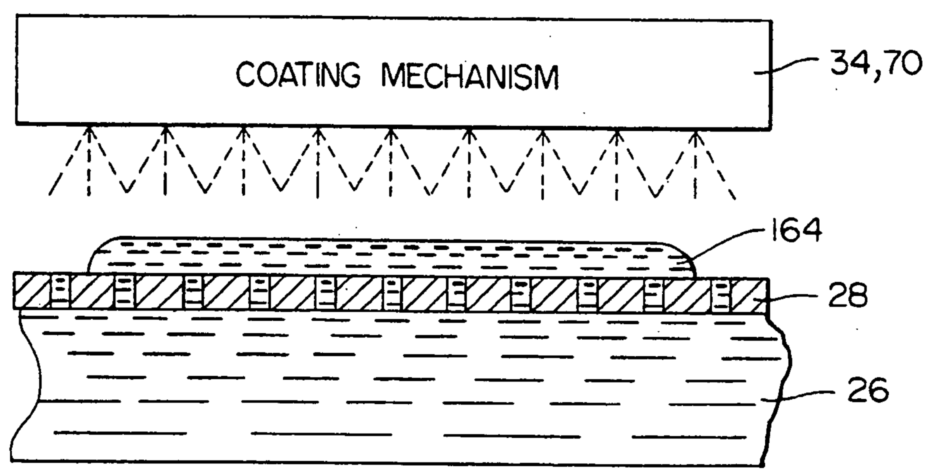


FIG. 9

STEPS 2 & 3

SOLIDIFY FIRST ARTICLE CROSS-SECTION AND RAISE SCANNER HEAD (AND COATING MECHANISM) TO THE NEXT FOCUS LEVEL.

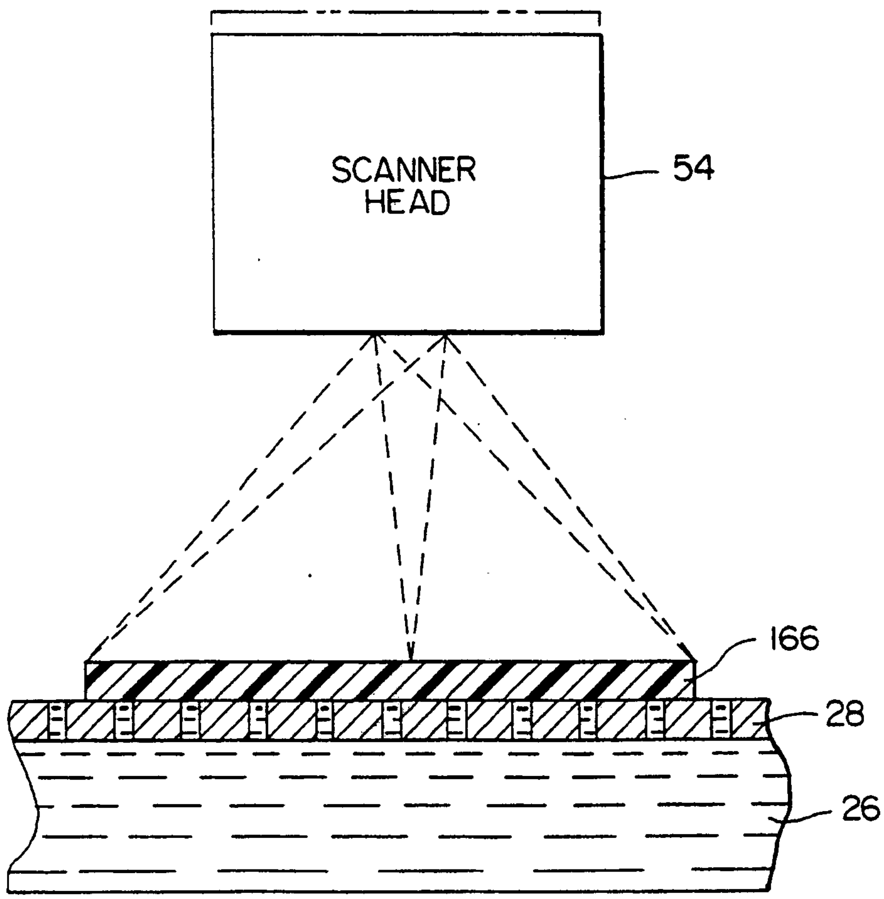


FIG. 10

STEP 4

RAISE LIQUID MEDIUM LEVEL ONE LAYER TO FORM MENISCUS AROUND SOLIDIFIED FIRST ARTICLE CROSS-SECTION.

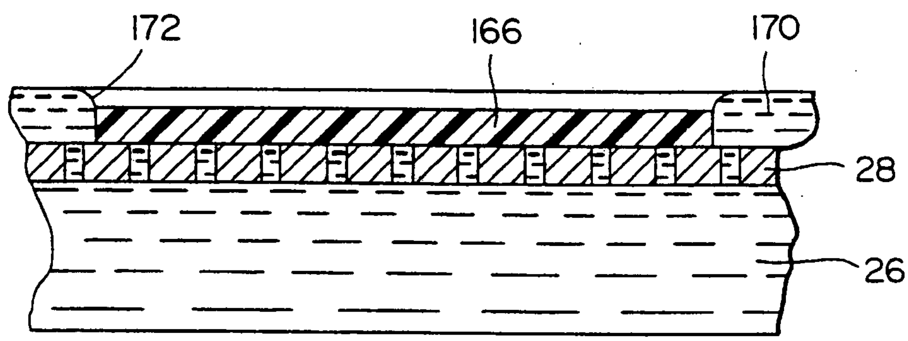


FIG.11

STEP 5

COAT NEXT LIQUID MEDIUM LAYER ON SOLIDIFIED FIRST ARTICLE CROSS-SECTION.

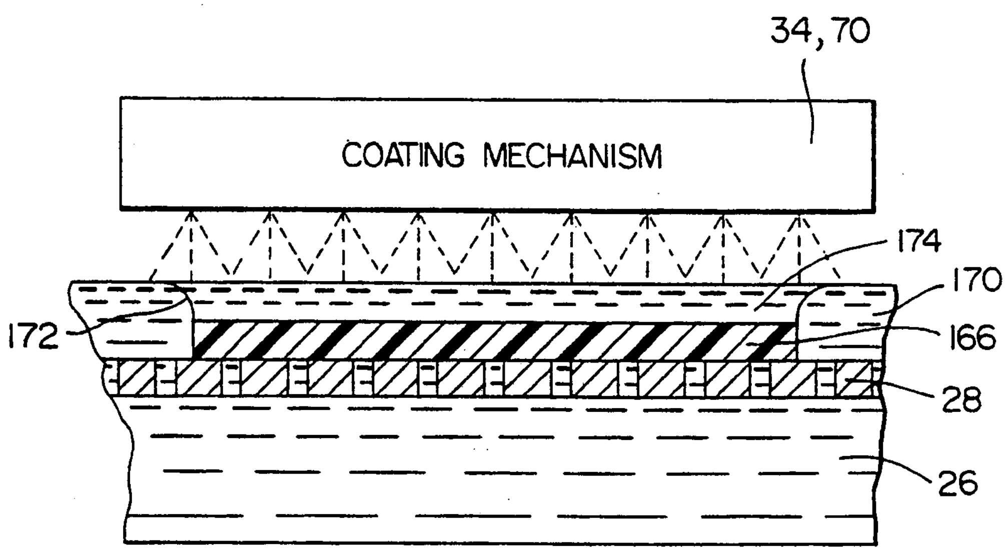


FIG. 12

STEP 6

MENISCUS BREAKS AND LIQUID MEDIUM LAYERS MERGE.

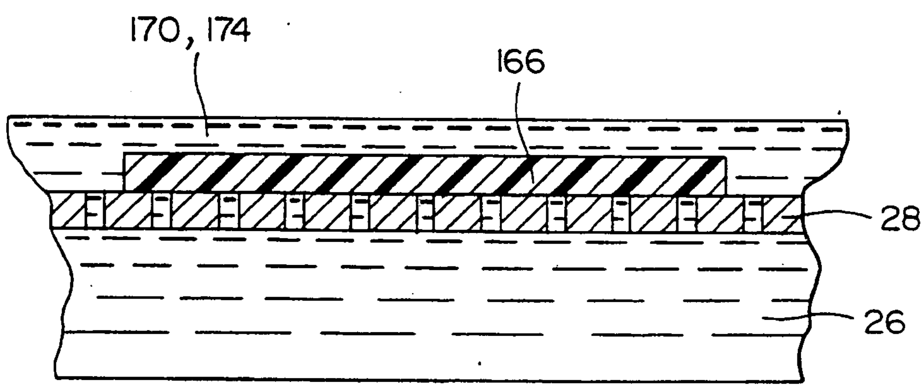
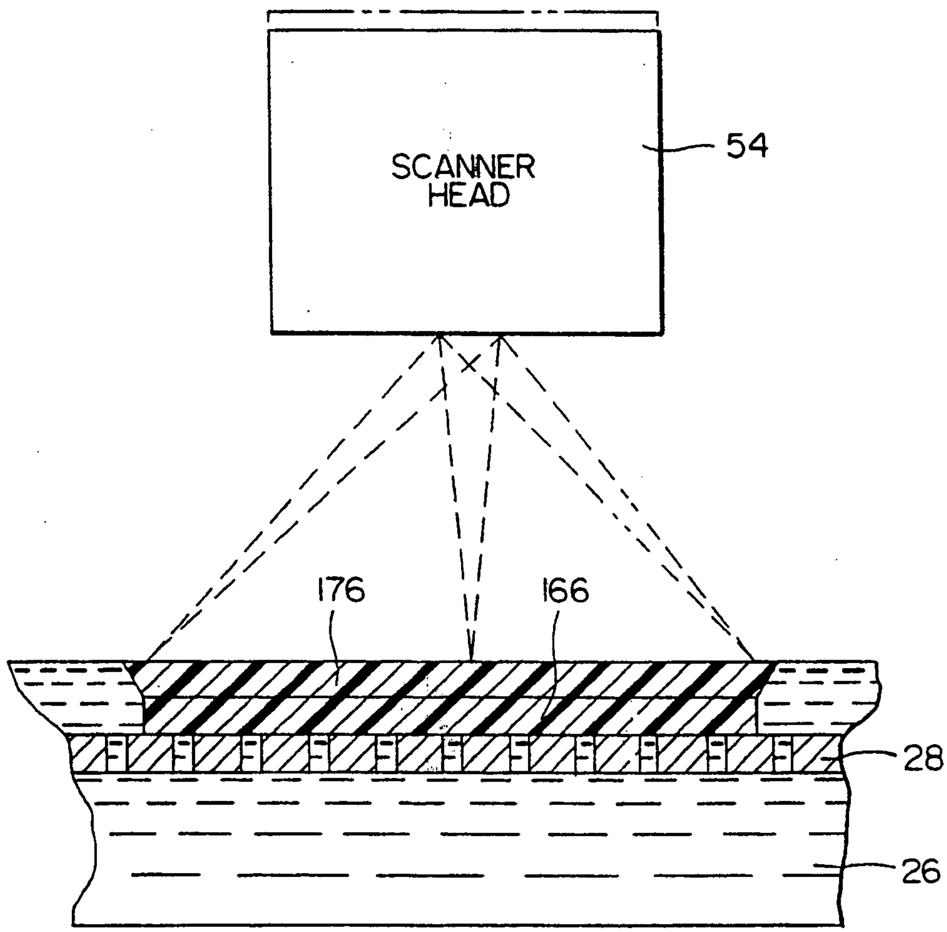


FIG. 13

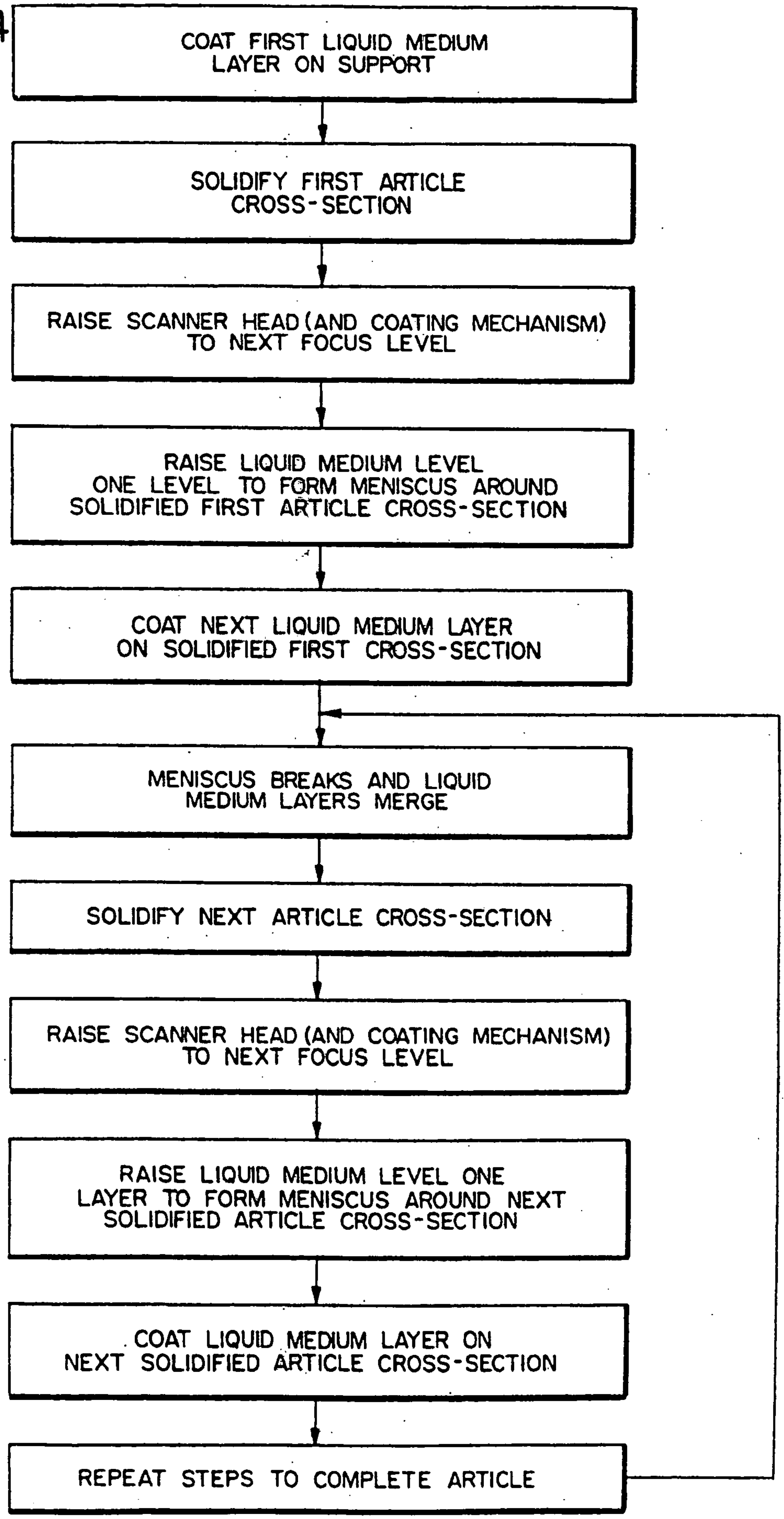
STEPS 7 & 8

SOLIDIFY NEXT ARTICLE CROSS-SECTION AND RAISE SCANNER HEAD (AND COATING MECHANISM) TO THE NEXT FOCUS LEVEL.



REPEAT LIQUID MEDIUM LEVEL RAISING, COATING, SOLIDIFYING AND SCANNER HEAD (AND COATING MECHANISM) RAISING STEPS TO COMPLETE ARTICLE.

FIG. 14


COAT FIRST LIQUID MEDIUM LAYER ON SUPPORT
SOLIDIFY FIRST ARTICLE CROSS-SECTION
RAISE SCANNER HEAD (AND COATING MECHANISM) TO NEXT FOCUS LEVEL
RAISE LIQUID MEDIUM LEVEL ONE LEVEL TO FORM MENISCUS AROUND SOLIDIFIED FIRST ARTICLE CROSS-SECTION
COAT NEXT LIQUID MEDIUM LAYER ON SOLIDIFIED FIRST CROSS-SECTION
MENISCUS BREAKS AND LIQUID MEDIUM LAYERS MERGE
SOLIDIFY NEXT ARTICLE CROSS-SECTION
RAISE SCANNER HEAD (AND COATING MECHANISM) TO NEXT FOCUS LEVEL
RAISE LIQUID MEDIUM LEVEL ONE LAYER TO FORM MENISCUS AROUND NEXT SOLIDIFIED ARTICLE CROSS-SECTION
COAT LIQUID MEDIUM LAYER ON NEXT SOLIDIFIED ARTICLE CROSS-SECTION
REPEAT STEPS TO COMPLETE ARTICLE

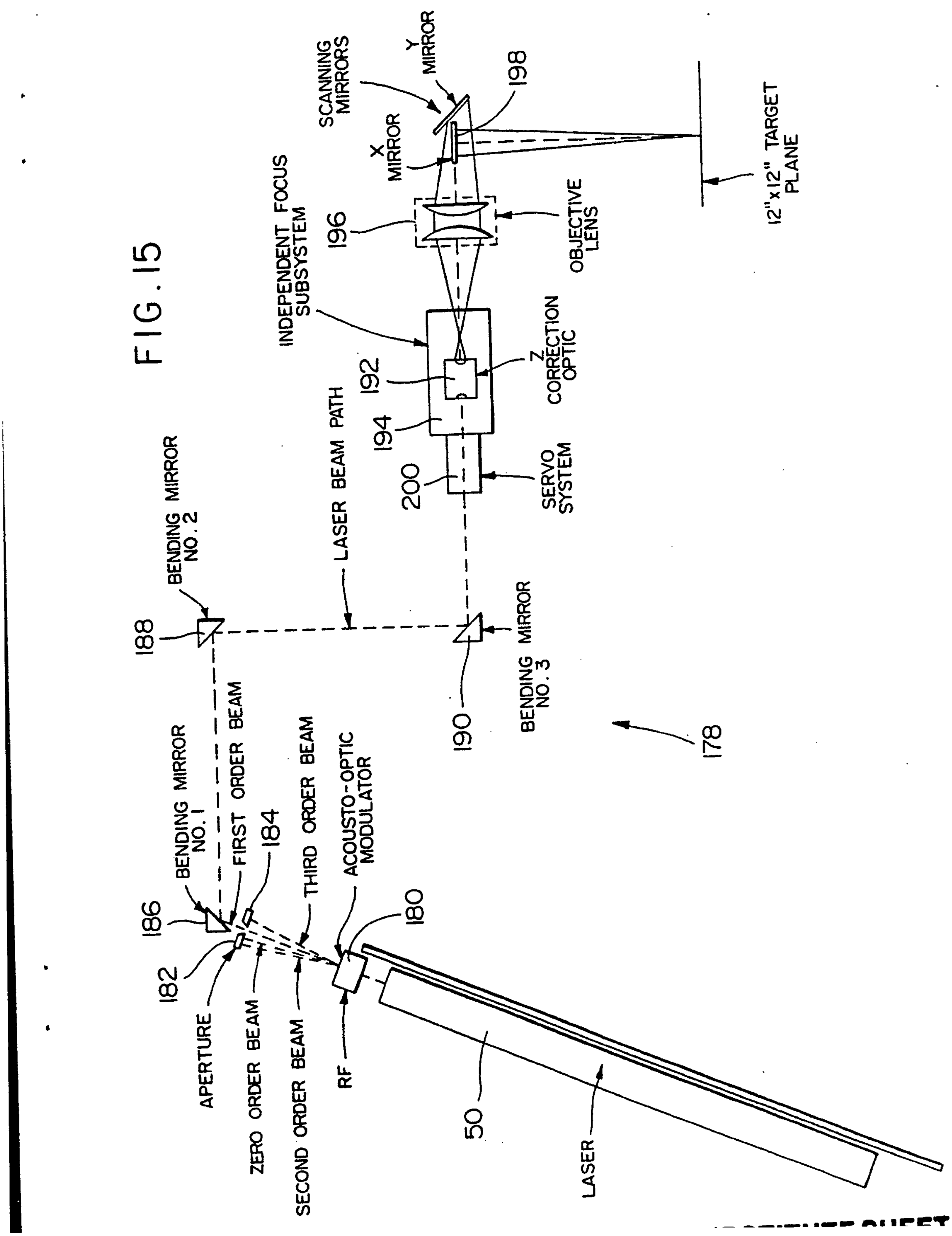
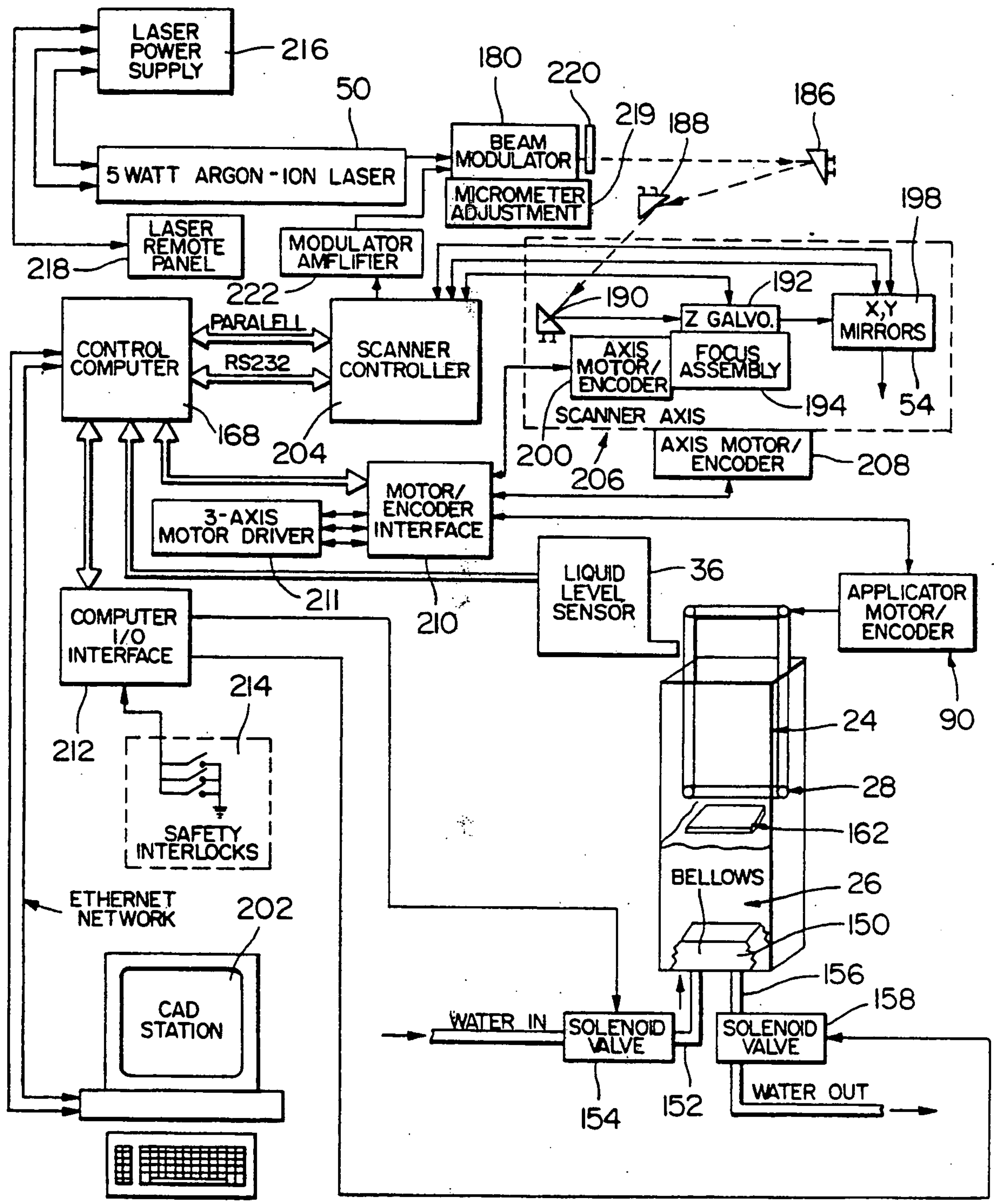

SCANNING MIRRORS
Y MIRROR
X MIRROR
198
12"x12" TARGET PLANE
INDEPENDENT FOCUS SUBSYSTEM
196
OBJECTIVE LENS
192
Z CORRECTION OPTIC
194
200
SERVO SYSTEM
LASER BEAM PATH
BENDING MIRROR NO. 2
188
BENDING MIRROR NO. 3
190
178
BENDING MIRROR NO. 1
FIRST ORDER BEAM
184
THIRD ORDER BEAM
ACOUSTO-OPTIC MODULATOR
186
180
182
APERTURE
ZERO ORDER BEAM
SECOND ORDER BEAM
RF
50
LASER

FIG. 15

FIG. 16



LASER POWER SUPPLY
216
180
220
50
219
188
186
BEAM MODULATOR
5 WATT ARGON-ION LASER
MICROMETER ADJUSTMENT
198
LASER REMOTE PANEL
MODULATOR AMPLIFIER
218
222
192
190
CONTROL COMPUTER
PARALELL
RS232
SCANNER CONTROLLER
Z GALVO.
X,Y MIRRORS
AXIS MOTOR/ ENCODER
FOCUS ASSEMBLY
194
54
168
SCANNER AXIS
204
200
AXIS MOTOR/ ENCODER
208
206
MOTOR/ ENCODER INTERFACE
3-AXIS MOTOR DRIVER
LIQUID LEVEL SENSOR
36
211
210
APPLICATOR MOTOR/ ENCODER
COMPUTER I/O INTERFACE
214
24
90
212
28
SAFETY INTERLOCKS
162
BELLOWS
26
ETHERNET NETWORK
202
150
CAD STATION
156
158
WATER IN
SOLENOID VALVE
SOLENOID VALVE
WATER OUT
154
152

FIG. 17

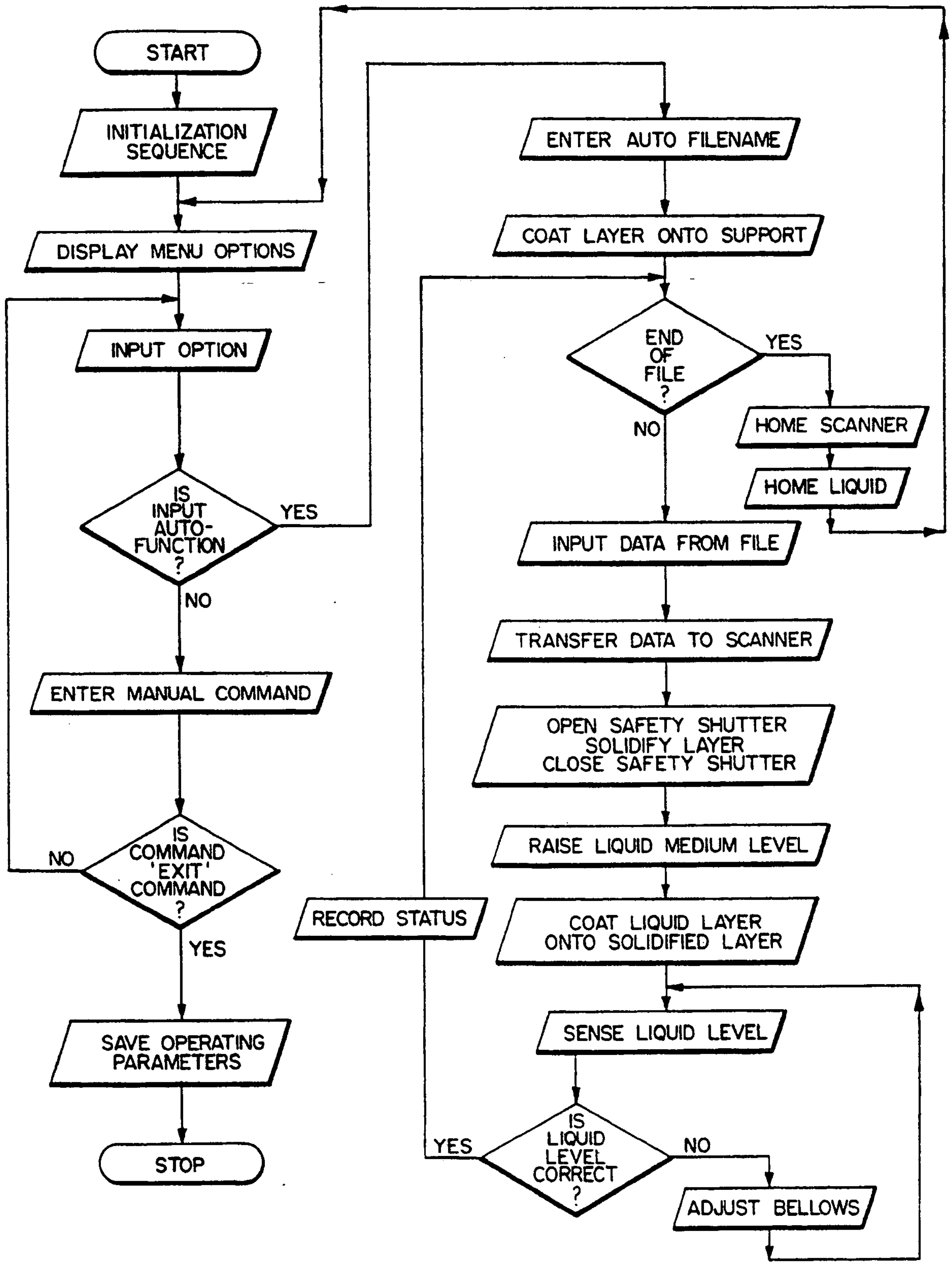

START
INITIALIZATION SEQUENCE
DISPLAY MENU OPTIONS
INPUT OPTION
IS INPUT AUTO-FUNCTION ?
YES
NO
ENTER MANUAL COMMAND
IS COMMAND 'EXIT' COMMAND ?
NO
YES
SAVE OPERATING PARAMETERS
STOP
ENTER AUTO FILENAME
COAT LAYER ONTO SUPPORT
END OF FILE ?
YES
NO
HOME SCANNER
HOME LIQUID
INPUT DATA FROM FILE
TRANSFER DATA TO SCANNER
OPEN SAFETY SHUTTER
SOLIDIFY LAYER
CLOSE SAFETY SHUTTER
RAISE LIQUID MEDIUM LEVEL
RECORD STATUS
COAT LIQUID LAYER ONTO SOLIDIFIED LAYER
SENSE LIQUID LEVEL
IS LIQUID LEVEL CORRECT ?
YES
NO
ADJUST BELLOWS

FIG. 18A

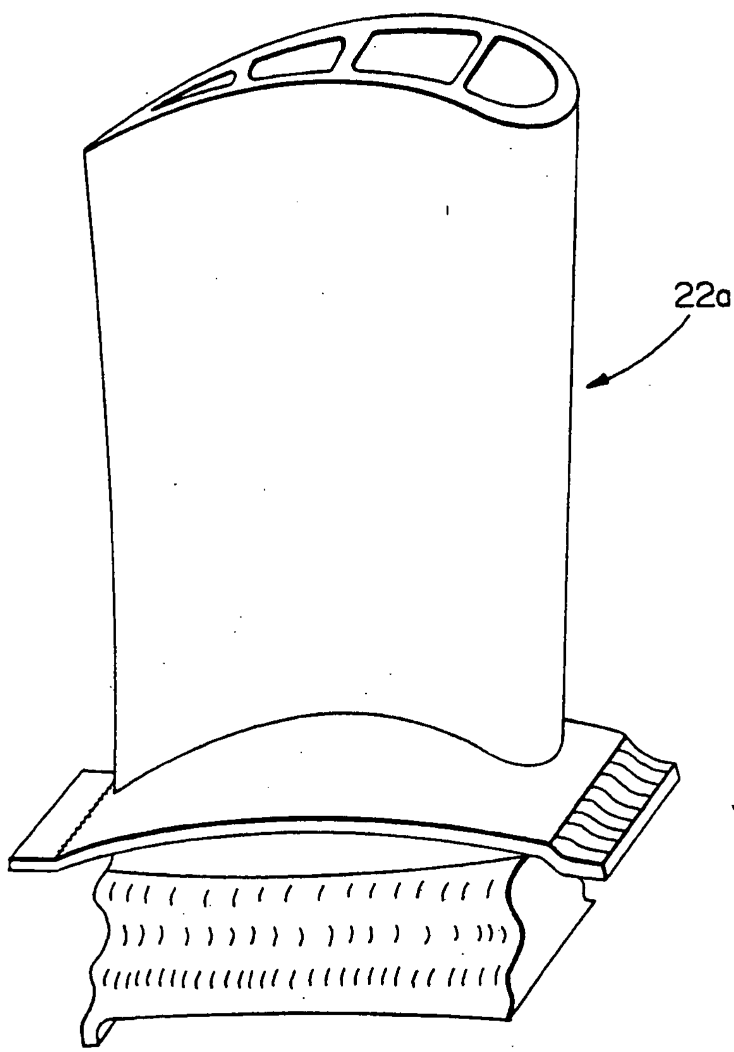


FIG. 18B

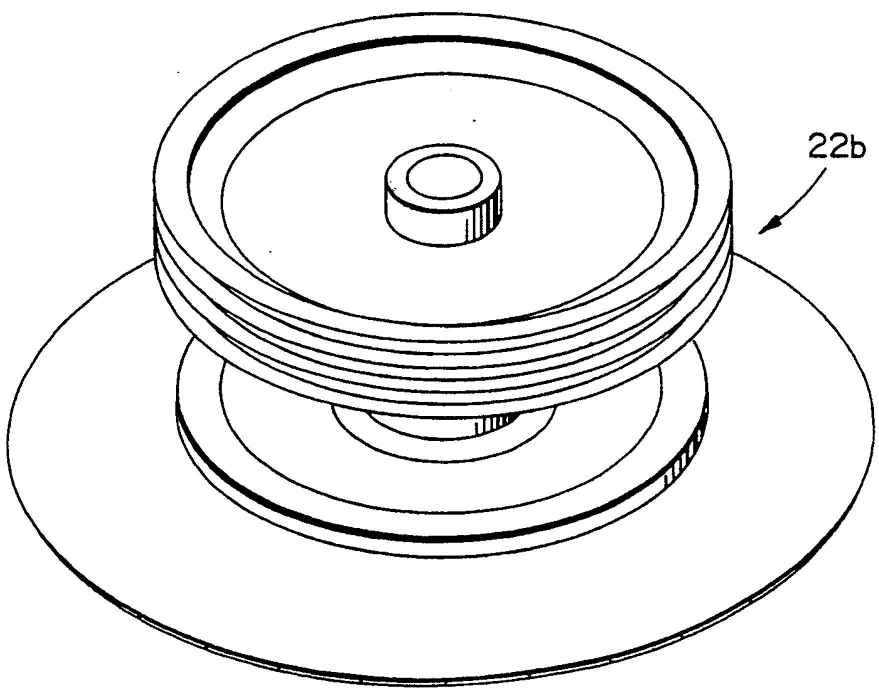


FIG. 19

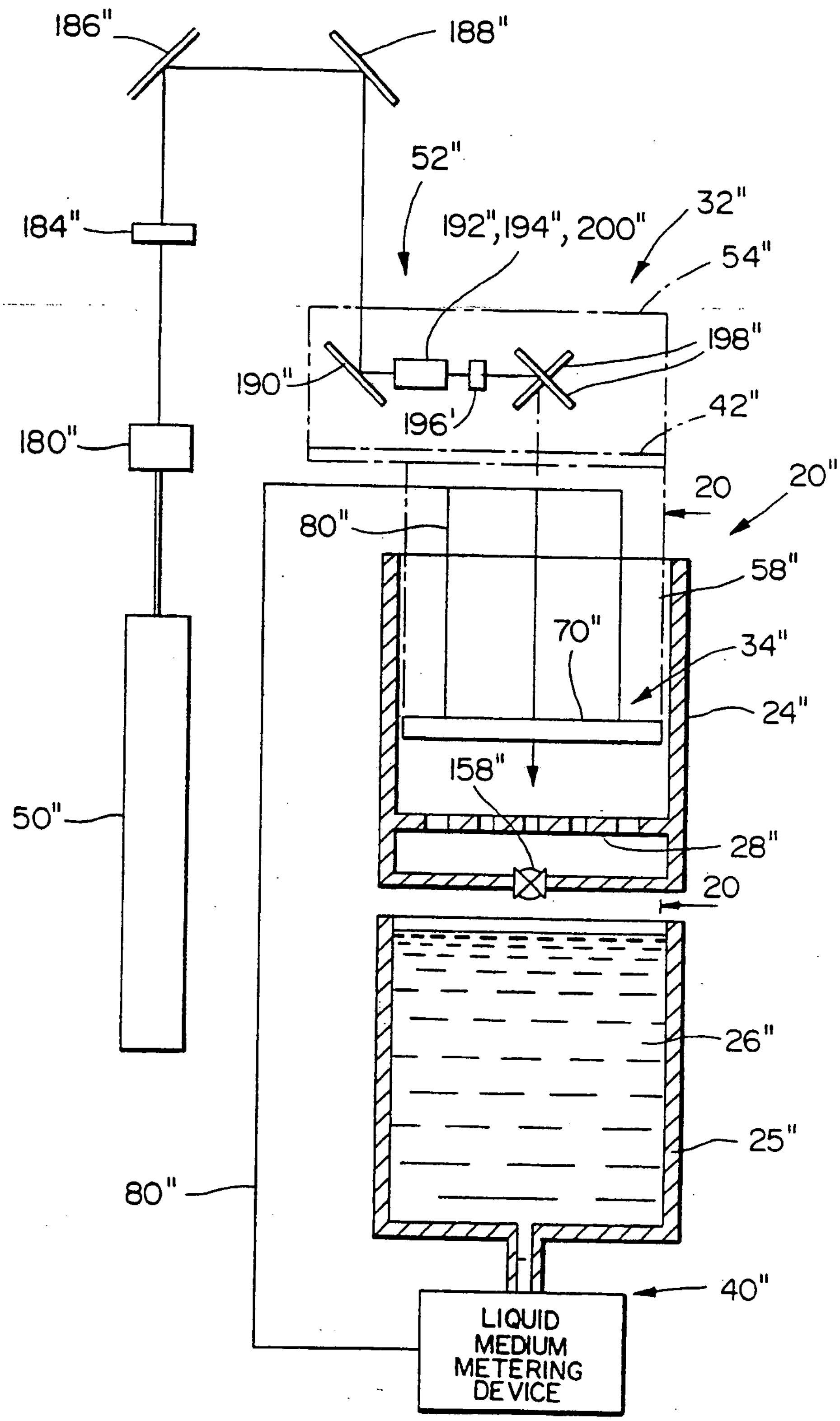

186"
188"
52"
192", 194", 200"
32"
54"
184"
198"
190"
196'
42"
180"
20
20"
80"
58"
70"
34"
24"
158"
50"
28"
20
26"
25"
80"
40"
LIQUID MEDIUM METERING DEVICE

FIG. 20

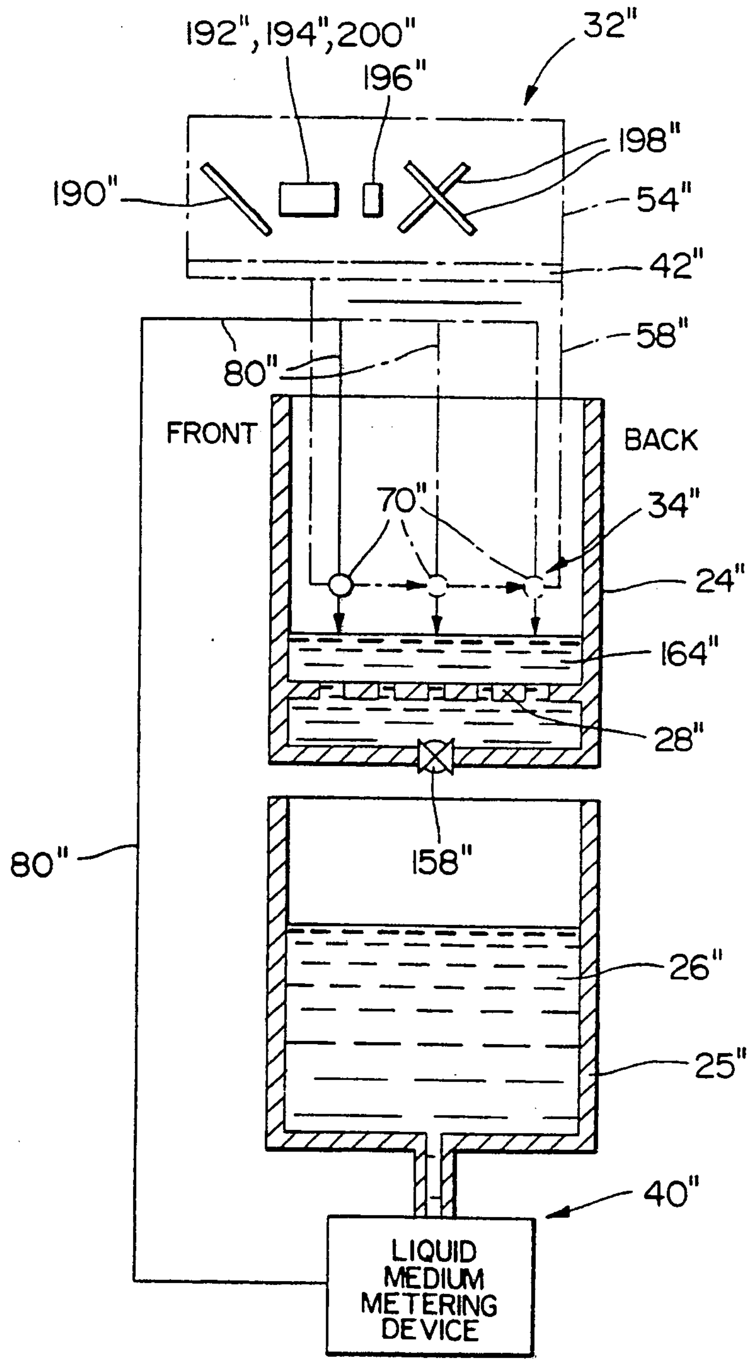

192",194",200"
32"
196"
198"
190"
54"
42"
58"
80"
FRONT
BACK
70"
34"
24"
164"
28"
158"
80"
26"
25"
40"
LIQUID MEDIUM METERING DEVICE

FIG. 21

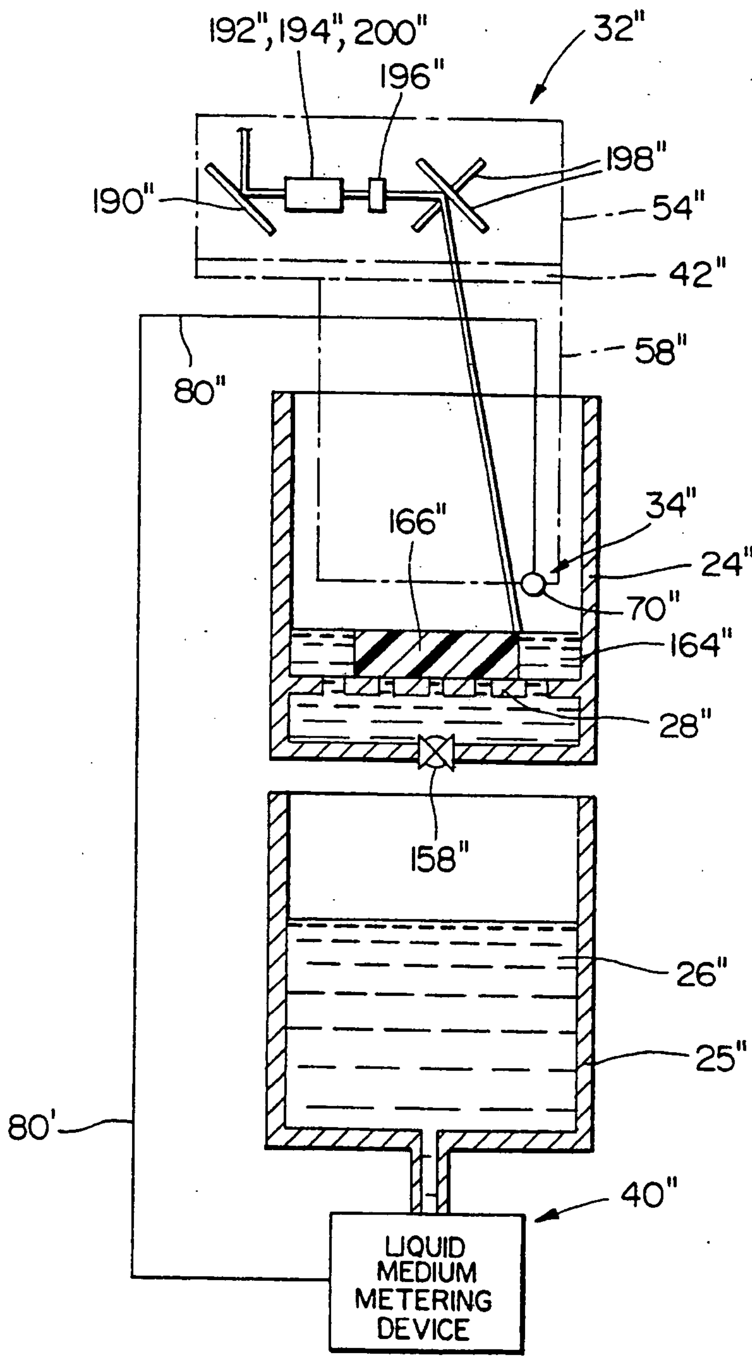

192",194",200"
32"
196"
198"
190"
54"
42"
58"
80"
34"
166"
24"
70"
164"
28"
158"
26"
25"
80'
40"
LIQUID
MEDIUM
METERING
DEVICE

FIG. 22

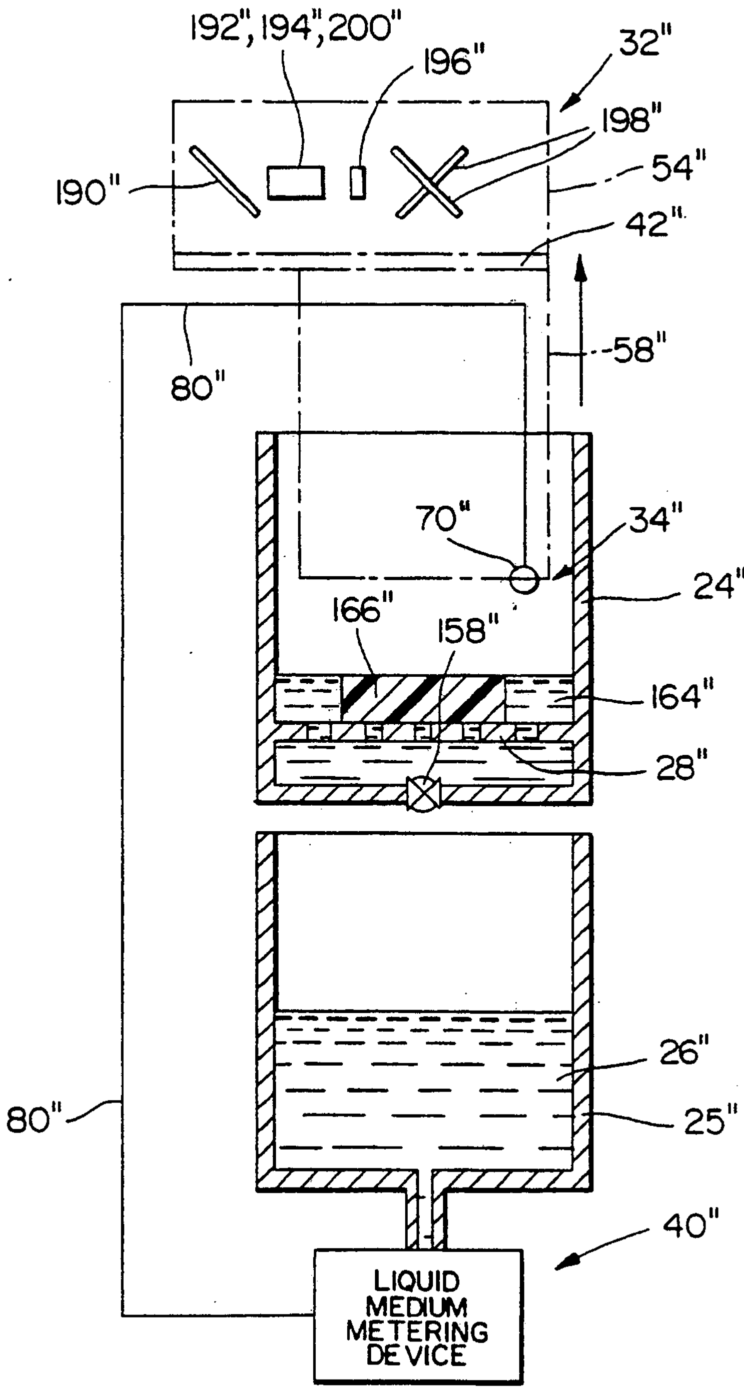

192",194",200"
196"
32"
198"
190"
54"
42"
80"
58"
70"
34"
24"
166"
158"
164"
28"
26"
80"
25"
40"
LIQUID
MEDIUM
METERING
DEVICE

FIG. 23

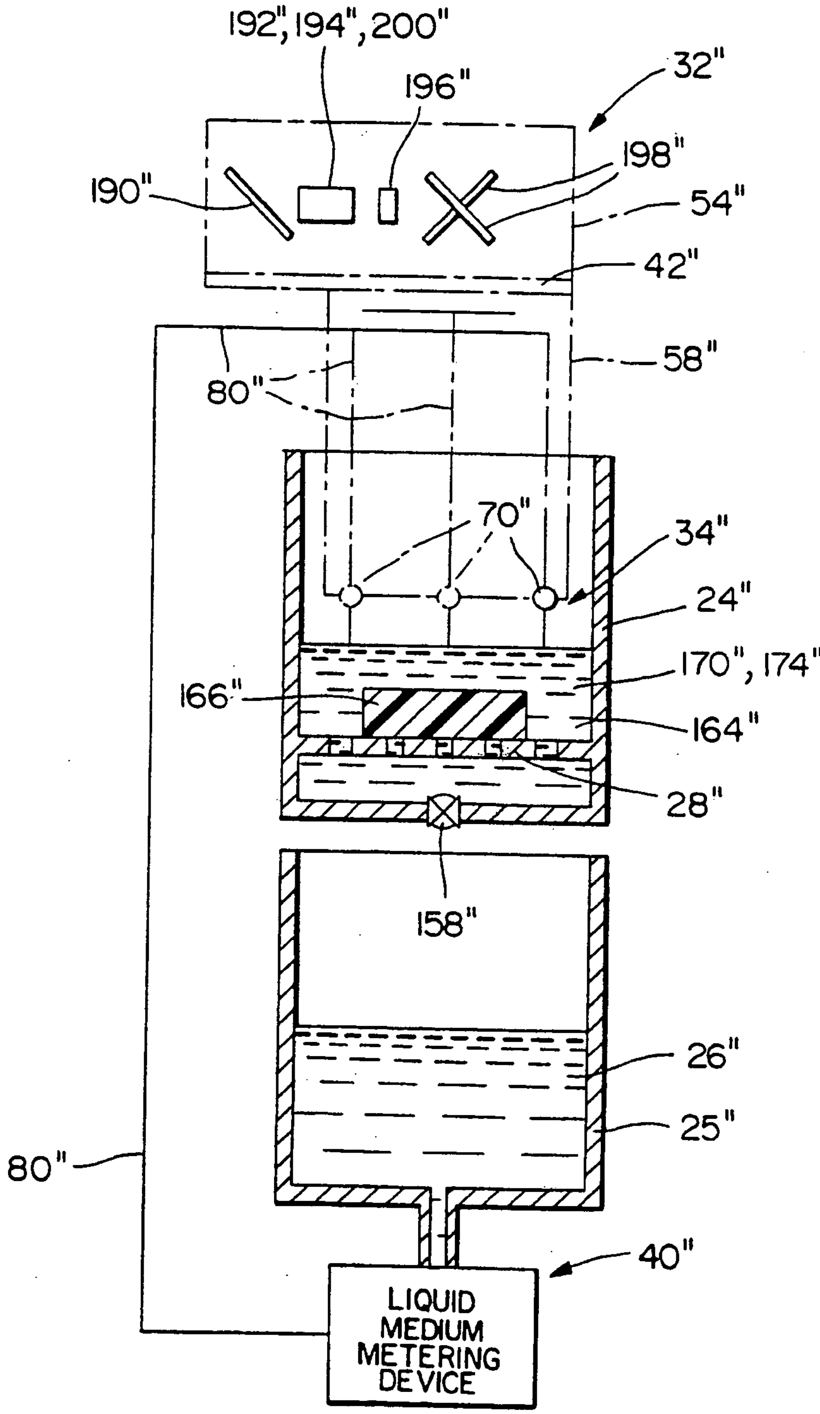

192",194",200"
196"
32"
198"
190"
54"
42"
58"
80"
70"
34"
24"
170",174"
166"
164"
28"
158"
26"
25"
80"
40"
LIQUID MEDIUM METERING DEVICE

FIG. 28

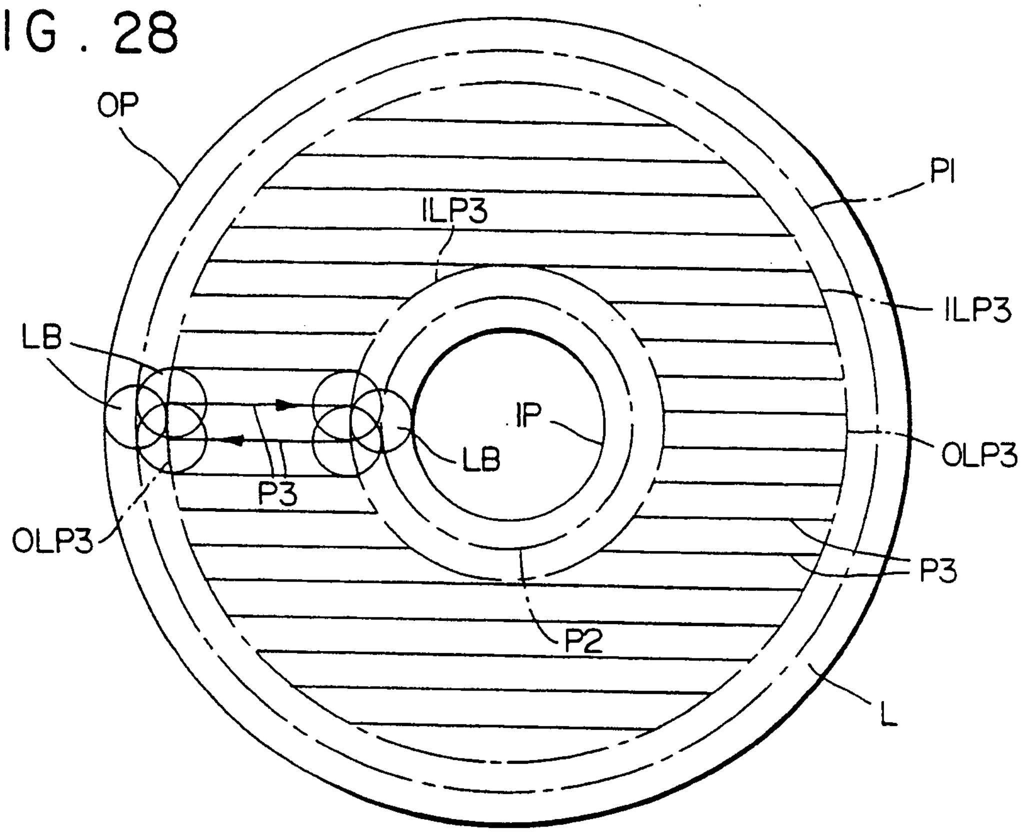


FIG. 29A

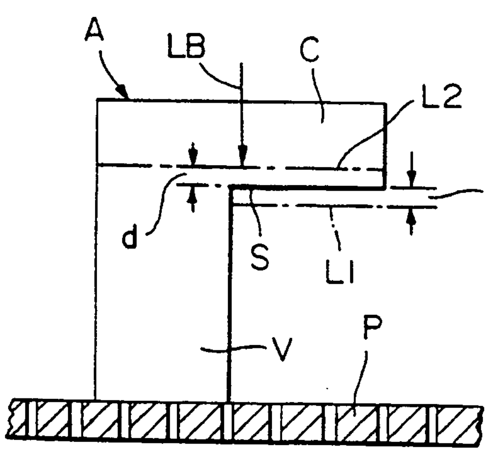


FIG. 29B

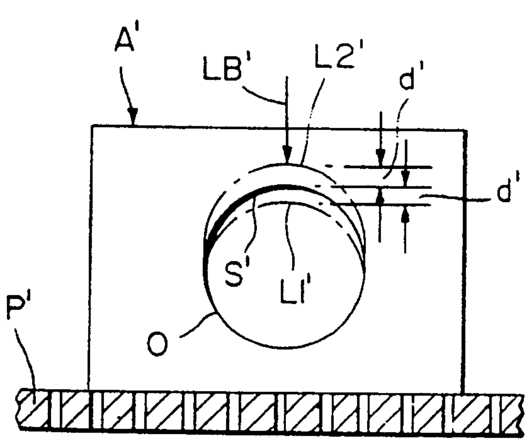


FIG. 30A

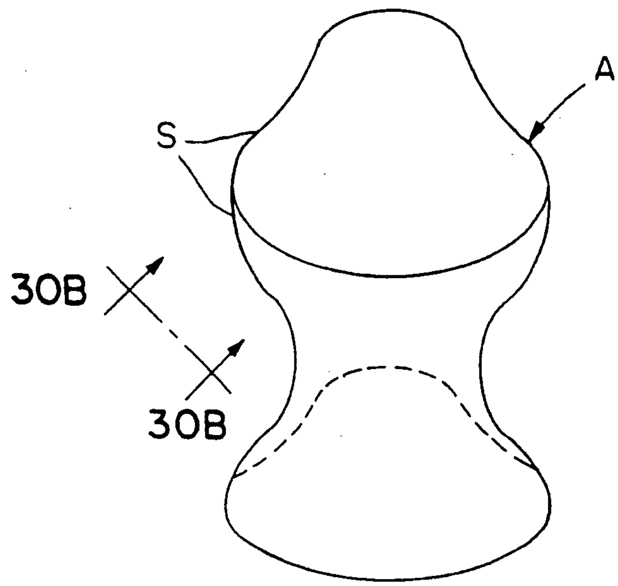


FIG. 30B
(PRIOR ART)

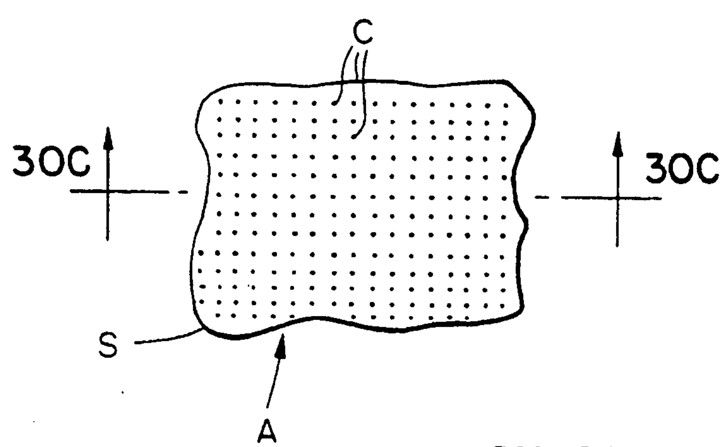


FIG. 30C
(PRIOR ART)

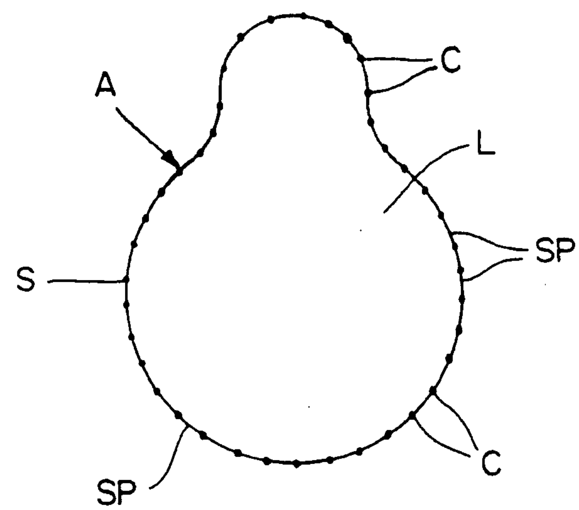
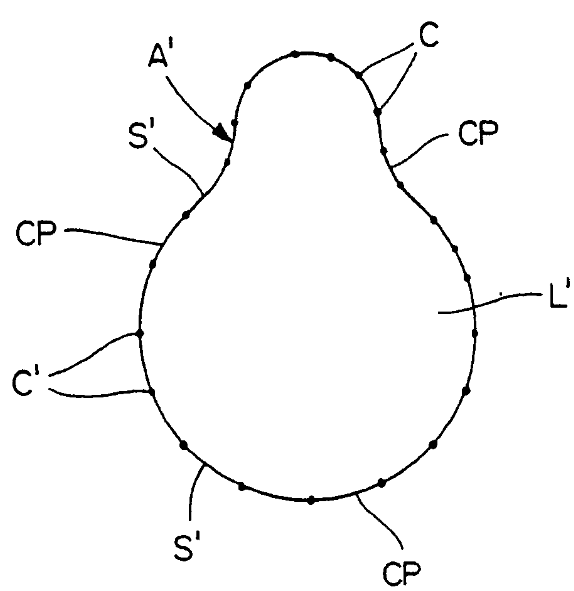


FIG. 30D



INTERNATIONAL SEARCH REPORT

International Application No. PCT/US91/00920

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC (5): B29C 35/08
U.S. CL: 264/22; 425/174.4

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
U.S. CL.	264/22,129,236,250,255,308 427/43.1, 54.1 425/112,174,174.4 156/58,59,242,272.8, 118/422,602,603,620,697 273.5,275.5,379.6

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X,P Y	US, A, 4,961,154 (POMERANTZ ET AL.) 02 October 1990 (See figures 4A,4B, and 11-13F; column 4, lines 66-68; column 8,lines 1-6 and lines 48-54; column 9, lines 35-46; column 16, lines 15-68; column 17, lines 1-68; and column 18, lines 1-8).	1-13,15,16 20-24,27,28 41-46, 50 14, 17, 29 36-40, 47
X Y	JP, A, 61-217,219 (MORIHARA ET AL.) 26 September 1986 (See entire document).	1-7,14-16 20-25,27,28 34,35,44,47,50 8-13,17,29, 30,36-43,45, 46
Y	WO, A, 89/09687 (HUGHES) 19 October 1989 (See page 5, lines 7-11; page 8, lines 33-35).	37-40
X	JP, A, 31,625 (TOKIEDA) 01 February 1989 (See entire document).	1,2,4-9,21-25,27,44-46
X	JP, A, 61-154,815 (MITSUI & CO. LTD) 14 July 1986 (See entire document).	1-5,7,10,11 21-24,27,41-44
X	JP, A, 62-101,408 (OSAKA PREFECTURE) 11 May 1987 (See entire document). (cont)	1,2,4-7,11 21-25,27,44

* Special categories of cited documents: [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
14 MAY 1991	26 JUN 1991
International Searching Authority	Signature of Authorized Officer
ISA/US	JAMES C. HOUSEL

Form PCT/ISA/210 (second sheet) (Rev.11-87)

FURTHER INFORMATION CONTINUED FROM THE SECOND SHEET

A	US, A, 2,775,758 (MUNZ) 25 December 1956 (See entire document).	1-50
A	US, A, 4,575,330 (HULL) 11 March 1986 (See entire document).	1-50

V. ☐ OBSERVATIONS WHERE CERTAIN CLAIMS WERE FOUND UNSEARCHABLE [1]

This international search report has not been established in respect of certain claims under Article 17(2) (a) for the following reasons:

1. ☐ Claim numbers , because they relate to subject matter [12] not required to be searched by this Authority, namely:

2. ☐ Claim numbers ...... , because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out [13], specifically:

3. ☐ Claim numbers__________, because they are dependent claims not drafted in accordance with the second and third sentences of PCT Rule 6.4(a).

VI. ☐ OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING [2]

This International Searching Authority found multiple inventions in this international application as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims of the international application.
2. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims of the international application for which fees were paid, specifically claims:
3. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim numbers:
4. ☐ As all searchable claims could be searched without effort justifying an additional fee, the International Searching Authority did not invite payment of any additional fee.

Remark on Protest

☐ The additional search fees were accompanied by applicant's protest.

☐ No protest accompanied the payment of additional search fees.

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